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CONTROL OF RADON AND DAUGHTERS IN URANIUM MINES AND CALCULATIONS ON BIOLOGIC EFFECTS

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Control of Radon and Daughters in Uranium Mines and Calculations on Biologic Effects

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Division of Special Health Services
Occupational Health Program

Foreword

A long range study under way by the Public Health Service since 1950 seeks to define the effects of uranium mining operations on the health of the miners and to derive data leading to the establishment of a healthful working environment.

Although no evidence of health damage has been found among American miners, the European experience points to possible serious health effects. As a preventive measure, steps were therefore taken early in the industry's growth to safeguard the health of the miners.

The current bulletin describes the results of the environmental study to date, together with the work of other investigators, with reference to methods of measuring atmospheric concentrations of radon and daughter products, the establishment of a safe working level for radon daughter products, and the development of effective control measures.

It is believed that the material presented will be found useful by the industry and others, particularly in evaluating health hazards and in deriving economically feasible control methods.

The Occupational Health Program again expresses its appreciation to the operating companies for their excellent assistance and cooperation in this study.

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Summary and Conclusions

Surveys of Colorado Plateau uranium mines have shown that 65 percent of the miners were exposed to concentrations of radon and its daughters comparable to those reported to exist earlier in European mines. Extensive control measures will be necessary to reduce these concentrations to the suggested working level.

Radiation dosage from breathing a radon-containing atmosphere arises principally from radon daughter products accompanying radon in the air. Substantial portions of these daughter products, RaA through RaC′, are retained in the lungs. The two alpha emitting isotopes of these daughters, RaA and RaC′, are the principal direct sources of radiation dosage. RaB and RaC retained in the lungs decay to RaC′ and therefore may be assumed to be indirect sources of alpha radiation. The beta and gamma rays from RaB and RaC are relatively of negligible importance.

Sufficient time has not elapsed to permit stating that no American miners have been injured by exposure to radon and its daughters. In certain central European mining regions it is possible that exposure to these elements may have been responsible for an increased incidence of bronchial carcinoma. The concentration of radon that was present in these European mines is only an estimate at best.

No reliable toxicity data exist from animal experiments that *allow* a calculation of permissible radon daughter concentrations for atmospheres breathed by man such as are encountered in mining operations. However, experimental data are available on the magnitude of the retention of radon daughter products in the respiratory system of experimental human subjects and animals. Moreover, measurements have been made in animals of the distribution of these retained daughter products in the respiratory system. With these data, and with a knowledge of the physical nature of radon, it is possible to estimate radiation doses to the respiratory system of human beings exposed to radon and its daughters.

There is much uncertainty in interpreting these calculations in terms of maximum permissible concentrations of radon daughter products in mines and industrial plants. Until biologic information is available which will assist in determining these concentrations, a working level is suggested for use in the uranium mining industry.

Radon in mines may be determined by measuring the alpha activity of air samples collected in these mines. Radon daughter product concentrations can be measured by determining the alpha or gamma

activity of membrane filters through which known volumes of mine air have been drawn.

The polonium content of urine may provide a measure of the total exposure of an individual to radon and radon daughters.

Investigations were performed into the effect of ventilation on concentrations of radon daughters under a variety of mine conditions. Moreover, limited studies were made of the concentrations in uranium mines as affected by mechanical ventilation, and varying outside air temperatures.

It would seem that the material presented in this report leads to the following conclusions:

1. A working level of 1.3×10^5 Mev of potential alpha energy per liter is suggested for radon daughter products. The recommended field method described in section V measures the total alpha energy which will be delivered by the decay of any mixture of RaA, RaB, and RaC through RaC'. A total concentration of these elements of 300 micromicrocuries per liter of air as determined by the field method will release 1.3×10^5 Mev of alpha energy.

2. To meet the working standard virtually all uranium mines will require mechanical ventilation during all seasons of the year.

3. In the uranium mines where ventilation is present, it is in most instances inadequate, often used only occasionally or after blasting, and is seldom delivered at a point close enough to the working face to be effective.

4. The amount of air necessary in a working place to reduce the radon daughter concentration to a given value can be estimated from determinations of the air-change rate and the atmospheric concentrations of radon daughters, or radon (section VI).

5. Reasonable amounts of ventilation will reduce the radon daughters to acceptable levels in uranium mines. Specific recommendations for ventilation are given in section VI.

6. Maximum use should be made of natural ventilation, but this cannot be relied upon to reduce concentrations to acceptable levels under all temperature conditions.

It is emphasized that the above recommendations apply only to present uranium mines with relatively nonextensive underground workings. If uranium mining operations approach other metal mines in size and activity, further study will be necessary to determine what practices beyond standard metal-mine ventilation are required to control the hazards from radioactive materials.

SECTION I

Introduction

A steadily mounting rate of uranium production has focused increasing attention on the health hazards associated with the mining of this strategic metal. Predominant among these hazards is exposure to radon, a dense gas emanating from the ore, together with the products which result from the radioactive decay of radon.

To date, neither records of human exposure to radon daughter products nor data from animal experimentation have been available in sufficient quantity to permit a determination of a maximum permissible concentration for these elements. It has therefore been necessary to establish a working level which appears to be safe, yet not unnecessarily restrictive to industrial operations. Such a level, it is believed, has been established and recommended in this bulletin.

This level was derived after careful consideration of expert opinion and study of data from other radioactive doses known to produce biologic damage. It is believed that the factor of safety in this level is sufficiently great to prevent recognizable damage to the lung tissue in the normal healthy worker.

Exposure to radon and its daughters has been widespread throughout the mining industry and has not been confined to uranium mines. The Public Health Service and other agencies are now making observations on large groups of miners who have worked for many years in concentrations of radon daughters similar to the working level suggested in this bulletin. The final results of these studies will assist in establishing a threshold limit. Until such studies are completed, however, the Occupational Health Program recommends that the industry make every effort to reduce the atmospheric concentrations in the mines to, or below, the suggested working level.

This report reviews three principal sources of evidence that have led to the establishment of this level, namely, (1) results of human exposure, (2) results of experimental animal exposure to toxic radon levels, and (3) predicted human tissue dosage from calculations based upon known physical constants of radon and its daughter products and upon experimental studies of the retention of radon and radon daughter products in the respiratory system of human and experimental animal subjects.

Occurrence in Uranium Mines of Radon and Daughter Products of Radon

Uranium ores contain, in addition to uranium, all of the other members of the radioactive series of which it is the parent. The elements of this family considered to be potentially most hazardous to uranium miners are radon, polonium[218] (RaA), lead[214] (RaB), bismuth[214] (RaC), and polonium[214] (RaC').

Radon enters mine atmospheres by diffusion from the ore bodies, or by being carried into the mines by ground water. Radon though only slightly soluble in water can travel long distances underground to be released when the pressure on the water is lowered. The amount of radon that will be present in any part of a mine is determined by the rate of emanation into the mine, the rate of removal by ventilation, and radioactive decay of the gas. The immediate daughters of radon all have short half lives and thus will rapidly grow in an atmosphere containing radon even though freshly emanated radon is free of them. However, it requires about three hours for equilibrium to be reached in this series, and therefore the atmospheric concentrations of these elements are readily affected by ventilation. Under these conditions, it is rare to find equilibrium amounts of radon and its daughters present in mines.

During the study of the uranium mines, an effort was made to obtain atmospheric samples for radon and for RaA and RaC' in all the operating mines in the Colorado Plateau. However, in the absence of central records and since many of the smaller mines are worked only sporadically, it proved impracticable to achieve total coverage. During the summer of 1952, samples were obtained in 157 mines located in Colorado, Utah, Arizona, and New Mexico. It is believed that the mines surveyed employed a large percentage of the workers and that the concentrations of radioactive gas and dust found were representative of those occurring throughout the industry.

The samples were collected and analyzed by the methods described in section V. The figures given for RaA plus RaC' were obtained by the first field method described in that section, which is accurate only if secular radioactive equilibrium exists among the several daughters of radon at the time the sample is taken. For a full discussion of the procedures used, reference should be made to section V.

The results of these samples are given in tables II–1 and II–2. The data have been consolidated and are presented by mining districts, showing the median, maximum, and minimum concentrations that were found in the mines in each district. Table II–3 shows the number of mines and miners that fall into each of several ranges of atmospheric concentrations of radon daughter products.

TABLE II–1. *Concentration of radon daughters in mine atmospheres by mining area, 1952 survey, approximately 400 samples*

Area	Number of mines	RaA+RaC′, micromicrocuries per liter of air (μμc/l)		
		Median concentration	Maximum concentration	Minimum concentration
Bull Canyon	11	4,500	32,000	36
Calamity Mesa	10	1,800	17,000	66
Cottonwood Wash	7	520	26,000	<2
Durango	5	18	120	<3
East Reservation	9	100	3,200	11
Eastern Slope	1	8	8	8
Gateway	8	1,000	6,000	6
Grants	3	2,800	7,000	38
Gypsum Valley	4	9,000	18,000	500
Long Park	25	4,600	37,000	15
Marysvale	4	2,500	59,000	180
Moab	10	380	3,400	2
Monticello	2	950	1,900	15
Monument Valley	3	1,200	11,000	9
Outlaw Mesa	3	3,000	3,800	18
Paradox Valley	4	800	6,500	37
Polar Mesa	7	2,400	7,700	36
Slick Rock	25	1,100	30,000	<2
Temple Mountain	9	300	2,800	<2
Uravan	7	850	12,000	160

Tables II–1 and II–2 show that the atmospheric concentrations of radon and its degradation products in the mines varied over very wide ranges. The median values for each mining district are more representative of the situation existing at the time of the survey and are given to assist in interpreting the data.

Table II–3, which gives the distribution of mines by ranges of radon daughter concentrations, shows what conditions can be anticipated in uranium mines in which there are no planned measures to control the amounts of radioactive elements in the atmosphere. If 200 micromicrocuries per liter of RaA and RaC′ is taken as a tentative working level, table II–3 shows that control measures should be installed in the vast majority of the mines. For example, 55.4 percent of the

mines employing 64.0 percent of the miners, had atmospheric concentrations of a 1,000 or more micromicrocuries per liter, a concentration which calls for the immediate application of corrective measures.

TABLE II–2. *Concentration of radon in mine atmospheres by mining area, 1952 survey, approximately 100 samples*

Area	Number of mines	Radon, micromicrocuries per liter of air (μμc/l)		
		Median concentration	Maximum concentration	Minimum concentration
Bull Canyon	11	4,100	59,000	1,085
Calamity Mesa	6	570	23,000	70
Cottonwood Wash	4	4,500	9,900	3,100
East Reservation	6	170	2,200	100
Gateway	4	1,100	3,200	160
Grants	3	940	2,000	870
Gypsum Valley	3	14,700	18,000	1,200
Long Park	17	8,300	48,700	1,300
Marysvale	2	3,360	25,900	840
Monument Valley	3	5,900	6,100	170
Paradox Valley	2	----------	3,800	520
Polar Mesa	3	6,800	7,300	3,000
Slick Rock	11	3,900	22,000	130
Uravan	4	4,900	7,100	1,085

TABLE II–3. *Distribution of mines and miners by radon daughter concentration, 1952 survey*

RaA+RaC′, micromicrocuries per liter of air (μμc/l) [1]	Mines		Miners		Cumulative (miners)	
	Number	Percent	Number	Percent	Number	Percent
Total	157	100.0	733	100.0	----------	----------
0–99	35	22.3	116	15.8	733	100.0
100–499	27	17.2	117	16.0	617	84.2
500–999	8	5.1	31	4.2	500	68.2
1000–1999	17	10.8	140	19.1	469	64.0
2000–4999	36	22.9	153	20.9	329	44.9
5000–10,000	18	11.5	60	8.2	176	24.0
Over 10,000	16	10.2	116	15.8	116	15.8

[1] Arithmetic mean, all mines, 4290; median, all mines, 1300.

SECTION III

Physical and Chemical Characteristics of Radon and Daughter Products of Radon

Table III–1 gives the characteristics of the main sequence of elements by which the most abundant isotope of uranium, U^{238}, decays through radium and radon to a radioactively stable isotope of lead. Omitted from this table are U^{235}, the other natural isotopes of uranium and their daughter elements. The isotope, U^{235}, comprises 0.72 percent of the mass of normal uranium. This particular isotope undergoes radioactive decay at a somewhat higher rate, so that in normal uranium for every 100 alpha particles from U^{238} there will be 4.6 alpha particles from U^{235}.

Moreover, U^{235} is the parent element of a second radioactive series, the actinium series, that decays in a manner similar to U^{238} through radium and radon isotopes to a stable isotope of lead. It differs, however, in that the radon isotopes, Rn^{219}, has a half life of but 3.92 seconds. It follows that most of this radon isotope has decayed before it is air-borne, and thus contributes very little to the hazard of the mining or processing of crude uranium.

Figure III–1 shows diagramatically the radioactive decay path of Ra^{226} derived from U^{238} to stable lead.

Radon is only slightly soluble in water. Significant amounts, however, are often carried dissolved in water because a large amount of radon measured in terms of radioactivity is physically small. One curie of radon weighs approximately 6.5 micrograms.

The way in which radon divides itself between water and air has been determined experimentally and the results at various temperatures have been reported in terms of partition constants (*4*). At a temperature of 20° C., when an equilibrium state is reached, radon will be present in water at 0.23 times the concentration that it will have in air in contact with it. Thus, water containing radon will tend to lose radon to low-radon-content air with which it comes in contact; this release occurs rapidly, particularly if the water is flowing or is otherwise agitated.

Radon is much more soluble in fat than in water. Thus, at a temperature of 37° C., one gram of olive oil will retain in solution 125 times as much radon as compared with water. Because of the solubility of radon in fat, the gas will largely accumulate in the fatty

TABLE III–1. *The uranium disintegration series*

Common name or symbol	Isotope	Principal radiations	Alpha energy (Mev)	Beta maximum energy (Mev)	Gamma-ray quanta per disintegration	Average gamma-ray energy (Mev)	Half life [1]
Uranium 238	$_{92}U^{238}$	Alpha	4.18				4.49×10^{9} y
UX_1	$_{90}Th^{234}$	Beta		.205 80% .111 20%			24.1 d
UX_2	$_{91}Pa^{234}$	Beta		2.32 80% 1.5 13% 0.6 7%			1.17 m
Uranium 234	$_{92}U^{234}$	Alpha	4.76				2.48×10^{5} y
Ionium	$_{90}Th^{230}$	Alpha	4.68 75% 4.61 25%				8×10^{4} y
Radium	$_{88}Ra^{226}$	Alpha	4.78 94.3% 4.69 5.7%				1,622 y
Radon	$_{86}Rn^{222}$	Alpha	5.486				3.825 d
Radium A	$_{84}Po^{218}$	Alpha	5.998				3.05 m
Radium B	$_{82}Pb^{214}$	Beta Gamma		.65	.82	.295	26.8 m
Radium C	$_{83}Bi^{214}$	Beta Gamma		3.13 23% 1.67 77%	1.45	1.050	19.7 m
Radium C'	$_{84}Po^{214}$	Alpha	7.68				2.73×10^{-4} m
Radium D or Radiolead	$_{82}Pb^{210}$	Beta Gamma		.018	1.	.047	22 y
Radium E	$_{83}Bi^{210}$	Beta		1.17			5.02 d
Radium F	$_{84}Po^{210}$	Alpha	5.298				138.3 d
Radium G	$_{82}Pb^{206}$						Stable

NOTE.—All values are taken from information compiled by Hollander, Perlman, and Seaborg (*1*) except those for gamma radiations of RaB and RaC which have been reported by Evans and Evans (*2*). Numerical values for number of quanta of gamma radiation and quanta energy for these two isotopes are still uncertain. The product of number of quanta and quantum energy, that is the total gamma-ray flux, is known with greater certainty. Omitted from this table are branched disintegrations, unimportant from the health standpoint, that occur with Po^{218}, Bi^{214}, and Bi^{210}.

[1] y, year; d, day; m, minute.

tissues of human beings and animals exposed to it. Since fat is contained in blood, radon is more soluble in blood than in water. Under equilibrium conditions blood in contact with air will contain about 0.45 times as much radon per cubic centimeter of blood as compared with a like volume of air (*5*).

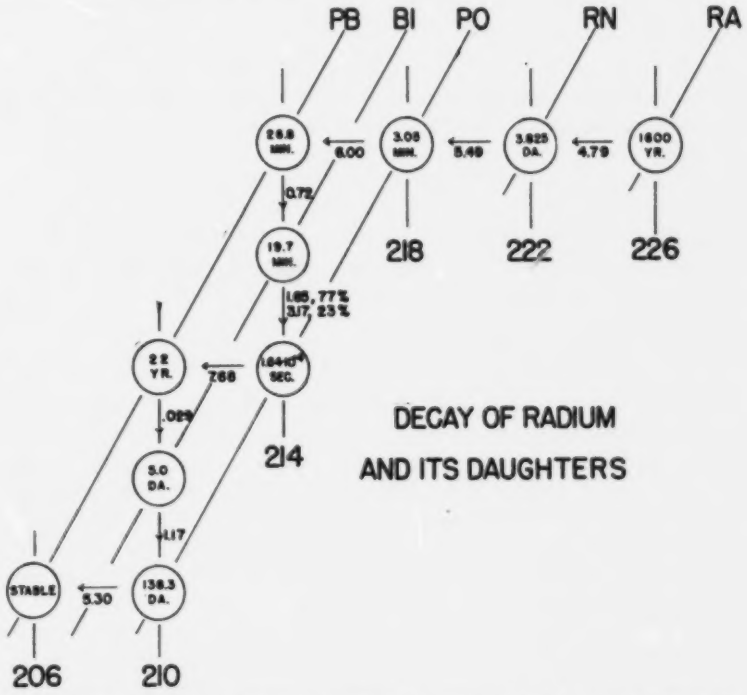

FIGURE III–1.—*Radioactive decay of radium 226 to stable lead 206 after Hursh (3). Alpha decay proceeds horizontally toward the left; beta decay proceeds vertically downward. Main alpha particle energies and maximum beta particle energies are noted adjacent to the arrows. Half lives are given within the circles.*

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SECTION IV

Tolerance Calculations for Radon and Daughter Products of Radon

Since there are insufficient data to permit the establishment of a final maximum permissible atmospheric concentration of radon and its immediate daughters, it is possible to arrive at only a tentative level, subject to re-evaluation on the basis of further evidence. Such evidence includes that available from histories of human exposure appearing in the records, results of animal experiments involving exposure to radon, and estimates of the radiation dose from inhaled radon and radon degradation products.

HISTORIES OF HUMAN EXPOSURE

Evidence of human exposure to radon resulting in recognizable health damage is almost entirely confined to the Schneeberg mining region of southern Germany and the adjoining Joachimsthal region of what is now Czechoslovakia. In 1937 Teleky (*6*) reported that some 30 percent of deaths of miners coming to autopsy were due to bronchial carcinoma. Additional evidence summarized by Lorenz (*7*) suggests that as high as 30 to 50 percent of all deaths among miners were caused by lung cancer.

The mines of this European area were the first important source of uranium and radium. When it began to be suspected that radon might be a hazard to miners, measurements of radon concentration were made. Evans and Goodman (*8*), in reviewing these measurements, concluded that the average concentration in these mines was about 1×10^3 micromicrocuries per liter. On the basis that evidence indicated that radon concentrations centering on this value probably were the cause of lung cancer, Evans has suggested that the radon level in industrial establishments where radium was used should not be allowed to exceed on an average 10 micromicrocuries per liter. This value has come to be rather generally accepted as the maximum permissible concentration in codes regulating the use of radium in producing luminous indicators and watch dials.

It should be noted that some question exists regarding radon as a causative agent of lung cancer in these European mining regions. Also, substantial uncertainty exists as to the level and duration of

exposure that must occur to produce harmful effects in human beings. It has been reported that arsenic is present in these mines and that it may have been important as a tumor-producing agent (7). Reliable data are not available regarding the incidence of lung cancer in this region, and its incidence in other regions where radon was absent or present only in low concentrations.

Lung disease, in particular silicosis complicated by tuberculosis, has often been found among miners, and a high incidence of lung cancer could be experienced without detection. The long latent period, usually given as 10 to 30 years, for the development of radiation-induced cancer has also contributed to the difficulty of determining the incidence of this condition. Finally, the available radon concentration values for the mines may be doubtful, particularly since they were determined after the possible hazard from radon was recognized, perhaps after some steps had been taken to reduce the levels of the radon existing in the mines. Thus, the later mine measurements, even if accurate, may not represent earlier conditions.

RESULTS OF ANIMAL EXPERIMENTS ON RADON TOXICITY

Experimental studies of the toxic effects of radon on animals have so far been restricted to the acute phase. These studies have been limited in that their short duration has precluded the possible production of lung cancer in animals. Through the removal of radon degradation products from the experimental atmospheres, these studies have also been largely confined to the effects of radon alone. Thus, on the basis of these studies, no deductions, not even of a tentative nature, may be made regarding the tolerance of the human respiratory system to long-term radon exposure.

However, one finding generally supported by animal experiments may be considered of special significance. Animals that die as a result of radon exposure extending to not more than a few days, do so, not because of local radiation effects on the lungs, but rather because of radiation effects on the hemopoietic system.

The results of previous experiments have been summarized and new results leading to an experimental LD_{50} for mice have been reported (9). These experiments, in which CAF mice were exposed to radon at a concentration of 2.2×10^6 micromicrocuries per liter (daughter-product free) for varying periods of time indicate that a one-hour exposure to a radon concentration of 7.5×10^9 micromicrocuries per liter would be expected to kill in 30 days one-half the exposed mice of this strain.

Calculations based upon this experimental result indicate that local radiation to the human respiratory system, rather than the effect of radon transported by blood and lymph to other parts of the body, will probably become recognized as the factor setting the human tolerance to chronic exposure to radon and its daughters. This conclusion results from the following considerations:

The 30-day LD_{50} for mice exposed to X-ray or gamma-radiation is about 600 r. The weekly maximum permissible dose for human beings is 0.3r, or 0.3/600 or 1/2,000 of the LD_{50} value for the mouse. Similarly it may be assumed that 1/2,000 or 0.0005 of the LD_{50} dose of radon for mice would be an acceptable weekly radon dose for human beings. This dose is 0.0005×7.5 mc/l$=3.75 \times 10^{-3}$ millicurie per liter, or 3.75×10^{-6} curie per liter for one hour per week. Assuming continuous exposure over a 40-hour working week, this level becomes $3.75/40 \times 10^{-6} = 9.4 \times 10^{-8}$ curie/liter. For continuous exposure for the 168 hours a week the value is 2.23×10^{-8} curie/liter of air.

These values may be high since one suspects, from studies such as those by Blair (*10*), that there may be much more irreparable damage from alpha rays such as are produced by radon and its daughters, than from beta or gamma rays. If the above values are decreased by a factor of ten to take this effect into account, the acceptable human radon concentration, based upon the effects of radiation upon the hemopoietic system, becomes for continuous exposure 2.23×10^{-9} curie per liter. This value is substantially higher than permissible levels for human exposure to the respiratory system arrived at by other considerations discussed in detail later.

TISSUE DOSAGE ESTIMATES

Dosage to tissues from ionizing radiations are usually estimated in terms of rep or rad units. The rep (roentgen equivalent physical) represents a radiation dose to a tissue such that the ionization produced in the tissue would be the same as from one roentgen of X-ray or gamma-radiation. In energy terms, one rep equals 93 ergs of energy expended by ionizing radiation per gram of tissue. The rad (*rad*iation) adopted as the unit of absorbed dose of ionizing radiation by the Seventh International Congress of Radiology held in Copenhagen in 1953, is 100 ergs per gram of absorbing material and thus is equivalent to approximately 1.075 rep.

The radiation received by the tissues of a human being exposed to an atmosphere of radon and its daughter substances is derived from two distinct sources: (1) Radon present as a gas; and (2) the radioactive daughter products of radon present in particulate form.

Inhaled Radon

Radon, when it is inhaled into the human respiratory tract, in undergoing radioactive decay, produces alpha particles in an amount proportional to the concentration of radon in the air. The fate of the first daughter product of this decay, Radium A, another alpha emitting isotope with a half life of 3.05 minutes, is not precisely known. RaA is an isotope of polonium, and experiment has shown that in air it becomes positively charged during recoil at the time that it is formed. It is reasonable to suppose that, at least in the smaller air passages and alveoli of the lungs, it rapidly comes in contact with the tissue lining the air chamber by a combination of brownian movement, electrical forces, and air currents, and remains there. At least this assumption is conservative in the sense that it leads to a maximum possible tissue dosage from radon.

The fate of Radium A produced by radon disintegration in the larger passageways of the respiratory system is more uncertain. Evans (*11*) has assumed that it is deposited on the walls of these passageways. This assumption in a dosage calculation leads to higher values than most other assumptions with reference to the radiation dosage to the epithelial tissue lining such passageways.

Radium A in turn decays through Radium B and C to another alpha emitter, Radium C′. The assumption that gives rise to the largest dose from RaC′ is that all of these degradation products are retained in the lung until they undergo radioactive decay.

From these considerations it is possible to calculate the radiation dosage to the lung from inhaled radon and the daughter products arising from its radioactive decay in the body. The calculation and the assumptions upon which it is based are as follows:

1. Exposure to pure radon at a concentration of 1×10^{-11} curie per liter is continuous, 168 hours per week.

2. All degradation products of radon decaying in the lung are retained in the lung.

3. The weight of healthy human lungs, W_s, is 455 grams.[1]

4. The average air content of human lungs, V_s, is 2750 cubic centimeters.

From table III–1 the sum of the alpha ray energies of Rn, RaA and RaC′, is 19.16 Mev. The number of disintegrations per minute of radon in volume V_s at a concentration of 1×10^{-11} curie per liter is:

$$V_s\times2.2\times10^{12}\times1\times10^{-11}=60.5$$

[1] This weight is given by Spitzka (*12*) from a study of the lungs of criminals executed by electricity. Human lungs obtained following death from other causes are usually considerably heavier. The National Committee on Radiation Protection in its tolerance calculations assumes the weight of human lungs to be 1,000 grams.

The ionization energy released per minute is:

$$60.5 \times 19.16 = 1{,}167 \text{ Mev}$$

The dose per gram integrated over the 10,080 minutes of a 168 hour week is:

$$\frac{10{,}080 \times 1.167 \times 10^3}{455} = 2.59 \times 10^4 \text{ Mev/gram}$$

Since one erg equals 6.242×10^3 Mev, and one rep equals 93 ergs per gram, this dose becomes:

$$\frac{2.59 \times 10^4}{6.242 \times 10^3} = 0.0415 \text{ erg/gram/week}$$

or in rep:

$$\frac{0.0415}{93} = 4.46 \times 10^{-4} \text{ rep/week}$$

To the radiation from the air should be added the radiation from radon dissolved in the lung tissue. On the rather arbitrary assumption that radon is present in lung tissue at the same concentration that it would reach in blood in equilibrium with air containing radon at a concentration of 1×10^{-11} curie/liter, this amount of radon is 0.455×10^{-11} curie$\times$partition coefficient (0.45) or $.2 \times 10^{-11}$ curie.

And by calculation similar to those given above, based on the assumption that radon and its daughters remain in the lung tissue at this effective concentration during radioactive decay, the rep/week concentration from this dissolved radon and its daughters is 0.324×10^{-4} rep/week. This contribution is small compared with lung air. When totaled this dose is 4.78×10^{-4} rep/week.

The National Committee on Radiation Protection assumes, in making maximum permissible concentration recommendations, that 1 rep of alpha radiation equals 20 rem (roentgen equivalent man) (*13*). This assumption takes cognizance of the fact that alpha radiation, with its high specific ionization, is relatively more damaging to mammalian tissue than beta or gamma radiation. Based on this assumption, the lung dose per week calculated as above becomes 9.28×10^{-3} rem per week. In the above calculations the beta and gamma dosages from radon and its daughters have been neglected since they make an insignificant contribution to the calculated rem dosage.

The radiation dosage, due to radon and its daughters decaying in the lung, will be nonuniform in distribution. In particular, the higher dose will be received by the cell lining of the larger bronchi, which are exposed to the largest unobstructed air volumes containing radon and its daughters.

The radiation dose to an infinitely small cell suspended in a large volume of radon at a concentration of 1×10^{-11} curie/liter, containing

air in equilibrium with air-borne daughters, is the same measured in rep as the radiation dose to air itself. For dry air at 37° C., the calculation is as follows:

Radon disintegration per minute per liter of air:

$$2.2\times10^{12}\times10^{-11}=22$$

Energy released in alpha particles per minute:

$$22\times19.16=425 \text{ Mev}$$

Energy released per 168 hours:

$$4.25\times10^{2}\times.60\times10^{2}\times1.68\times10^{2}=4.28\times10^{6} \text{ Mev}$$

Weight of 1 liter of air at 38° C.:

$$1.1387 \text{ grams}$$

Mev/gram of air/week:

$$\frac{4.284\times10^{6}}{1.1387}=3.76\times10^{6}$$

Since 1 erg$=6.242\times10^{5}$ Mev and 1 rep$=$93 ergs/gram, 1 rep$=6.242\times10^{5}\times.93\times10^{2}=5.805\times10^{7}$ Mev/gram

The calculated radiation dose is therefore:

$$\frac{3.76\times10^{6}}{5.805\times10^{7}}=.0648 \text{ rep per week}$$

On the assumption of 50 percent geometry the alpha radiation dosage to the surface layer of completely exposed skin or mucous membrane would be one-half this value, or 0.0324 rep per week. Since the skin is normally protected by an inert cornified layer of sufficient thickness to stop all alpha particles, such exposure of living cells would occur only in skin denuded of cornified epithelium or in mucous membrane extended beyond the orifices of the body. The margin of mucous membrane at the lips may possibly be exposed enough to receive an appreciable portion of this radiation dose.

Inside the body the largest exposure of this type would occur in the large passageways of the respiratory system. Since the lung tumors of miners have been associated with the inhalation of radon and are supposedly of bronchogenic origin, it is of interest to calculate the radiation dosage to bronchial epithelium.

Assume a bronchus one centimeter in diameter, and long and straight enough that end effects will not affect the dosage to the central portion. The volume of a one-centimeter long portion of such a tube will be 0.786 cubic centimeter with an inner surface area of

3.142 square centimeters. The alpha ray energy released per week for radon at a concentration of 1×10^{-11} curie per liter in equilibrium with its daughters through RaC′ will be:

$$\frac{4.284\times10^{8}\times.786}{1\times10^{5}}=3.37\times10^{3}\text{ Mev}$$

Assuming all alpha ray energy is dissipated in the tissue lining the bronchus to a depth of 40 microns, and that this tissue has a specific gravity of one, the weight of irradiated tissue is:

$$1\times3.142\times4\times10^{-3}=1.257\times10^{-2}\text{ gram}$$

and the reps/week:

$$\frac{3.37\times10^{3}}{1.257\times10^{-2}\times5.805\times10^{7}}=0.0046$$

This value is 14.2 percent of the 50 percent geometry value and, furthermore, is somewhat high because of the neglect of alpha absorption in air and inversely linearly dependent upon the depth (mass) of tissue over which the radiation effect is averaged. Moreover, the calculated dose rapidly decreases as the diameter of the air passage for which the calculation is made decreases. In this connection Shapiro (*14*) has calculated, using slightly different assumptions, radiation doses for a variety of diameters of air passageways.

It is also possible to estimate the average dose received by all bronchial epithelium subjected to alpha particle bombardment from radon in equilibrium with its daughters through RaC′. To do this, in addition to the physical constants previously discussed, values are needed for the mass of the tissue within range of alpha particles produced in the bronchi of the human lungs and for the average air volume of such bronchi. Evans (*11*) has estimated these values for an adult right lung as 9.8 grams and 51.5 cubic centimeters, respectively, leading to an average of 5.3 cubic centimeters of air per gram of tissue. This estimate represents the weight of tissue corresponding to a circular shell of wall thickness of 35 microns, and a length and inside diameter corresponding to dimensions of the bronchial passages.

Earlier it was noted that the alpha ray energy released per liter of air per 168-hour week at a concentration of 1×10^{-11} curie per liter is 4.284×10^{8} Mev. Per gram of bronchial tissue this corresponds to $5.3\times10^{-3}\times4.284\times10^{8}=2.27\times10^{6}$ Mev/gram of tissue/week. In rep per week this amounts to $\frac{2.27\times10^{6}}{5.805\times10^{7}}=3.91\times10^{-2}$.

Inhaled Radon Daughter Products

Measurements made in undisturbed atmospheres containing, besides radon, normal dust loads in the range that human beings are likely to encounter, show that RaA is essentially in radioactive equilibrium with the radon producing it. The abundance of the next alpha emitting radioactive daughter substance, RaC′, separated from RaA by two generations of intermediate isotopes, is much more variable but is typically present in amounts in the range of 20 to 80 percent of the equilibrium value.

In the following calculations and discussion it is arbitrarily assumed that this value is 50 percent, a value close to the average reported by Tsivoglou, Ayer and Holaday (*15*) in a survey of uranium mines of the Colorado Plateau area. Experimental measurements have shown that when these daughter products are breathed into the human respiratory system, appreciable percentages are retained there. Measurements by Harley (*16*) and by Shapiro (*14*) give values that range from 25 to 75 percent.

The radiation dose from radon daughter products through RaC′ breathed into the human respiratory system can therefore be calculated on the following assumptions:

1. Radon level: 1×10^{-11} curie per liter.
2. RaA concentration, same as radon: 1×10^{-11} curie per liter.
3. RaB concentration, ½ radon: 0.5×10^{-11} curie per liter.
4. RaC concentration, ½ radon: 0.5×10^{-11} curie per liter.
5. RaC′ concentration, ½ radon: 0.5×10^{-11} curie per liter.
6. Retention of these daughter products in respiratory system: 25 percent.
7. Daughter products remain in the respiratory system until radioactive decay through RaC′ has occurred.

Under these conditions the radiation dose from RaA breathed into the lungs can be calculated as follows:

Total disintegrations of RaA in one liter of air containing RaA at a concentration of 1×10^{-11} curie per liter:

$$\frac{(\text{disintegrations/unit of time})\times\text{half life}}{.693}=\frac{22\times3.05}{.693}=96.8$$

The alpha energy of one disintegration of RaA and RaC′ = 6.000 + 7.68 = 13.68 Mev.

The energy released will therefore be:

$$96.8\times13.68=1.34\times10^{3}\ \text{Mev}$$

On the further assumption that a human being inhales 2×10^7 ml/day for a 24-hour day (*12*), for a 168-hour week the air inhaled will be:

$$2\times10^7\times7=1.4\times10^8 \text{ ml}=1.4\times10^5 \text{ liters/week}$$

The alpha energy released by the total decay of RaA in this air will be:

$$1.34\times10^3\times1.4\times10^5=1.87\times10^8 \text{ Mev}$$

Assuming 25 percent retention of these decay products in the respiratory system in conformity with the value measured by Shapiro for a human subject breathing air with a normal dust load, the total alpha ray energy dose to the lungs per week becomes:

$$1.87\times10^8\times.25=.469\times10^8 \text{ Mev}$$

Assuming complete deposition and decay through RaC′ in the lungs of this 25 percent retained RaA, and that the lungs weigh 455 grams, the average dose per gram to the lungs is:

$$\frac{.469\times10^8}{.455\times10^3}=1.03\times10^5 \text{ Mev/g}$$

or measured in rep:

$$\frac{1.03\times10^6}{5.805\times10^7}=.00178 \text{ rep}$$

The same calculations can be made for RaB and for RaC-RaC′.

For RaB alpha energy=7.68 Mev (due to its decay product RaC′)
Total disintegrations per liter of air at 100 percent equilibrium with radon:

$$\frac{22\times26.8}{.693}=\frac{5.9\times10^3}{.693}=8.51\times10^3 \text{ d/l}$$

The alpha energy is:

$$8.51\times10^3\times7.68 \text{ Mev}=6.66\times10^4 \text{ Mev}$$

Assuming further that the actual equilibrium value is 50 percent of the 1×10^{-11} curie per liter radon level, and that 25 percent of the degradation products are retained in the lungs during the decay through RaC′, the alpha energy dose to the lungs per liter of air breathed becomes:

$$6.6\times10^4 \text{ Mev}\times.50\times.25=.83\times10^4 \text{ Mev},$$

and the alpha dose per week to the lungs:

$$.83\times10^{3}\ \text{Mev}\times1.4\times10^{5}=1.16\times10^{8}\ \text{Mev}$$

The ionization dose in Mev per gram per week is:

$$\frac{1.16\times10^{8}}{.455\times10^{3}}=2.56\times10^{5}\ \text{Mev/g/week}$$

and the average dose in rep:

$$\frac{2.56\times10^{5}}{5.805\times10^{7}}=4.41\times10^{3}=.00441\ \text{rep/week}$$

Making a similar calculation for RaC, the rep dose is:

$$\frac{22\times19.7\times7.68\times1.4\times10^{5}}{.693\times2\times4\times.445\times10^{3}\times5.805\times10^{7}}=.00330\ \text{rep/week}$$

With the above assumptions the total alpha ray dose from RaA RaB, and RaC-RaC′ inhaled as particulates into the lungs is therefore:

From RaA, .00178
From RaB, .00441
From RaC, .00330
.00949 rep/week

This is larger than the dose due to inhaled radon and the daughters of this inhaled radon decaying in the lungs by a factor equal to:

$$\frac{9.49\times10^{-3}}{4.78\times10^{-4}}=19.9$$

This is to say, if the daughter products could be filtered from the air breathed, the average radiation dose to the lungs due to radon and its daughters would be reduced to 5.0 percent of the value for unfiltered air.

To calculate the average dose to radiated bronchial tissues from radon daughter products breathed into the lungs, there is required, in addition, a value for the portion of inhaled daughter products retained in the bronchi. Morgan (*17*) has suggested for calculation purposes that it be assumed that 50 percent of these daughter products retained in the lungs are taken out in the bronchial tree. On this assumption the alpha radiation dose from RaA, and RaB, and RaC retained in the bronchial tree will be:

From RaA, $0.469\times10^{8}\times0.5=0.235\times10^{8}$ Mev
From RaB, $1.16\times10^{8}\times0.5=0.580\times10^{8}$ Mev
From RaC, $0.855\times10^{8}\times0.5=0.428\times10^{8}$ Mev
1.25×10^{8} Mev

On the assumption used previously that the weight of bronchial tissue lying within effective range of the alpha rays of daughter products deposited in the bronchi is 20 grams, the radiation dose in Mev per week from alpha radiation per gram of bronchial tissue will be:

$$\frac{12.5\times10^7}{20}=0.625\times10^7 \text{ Mev/gram}$$

and the dose in rep units will be:

$$\frac{0.625\times10^7}{5.805\times10^7}=0.108 \text{ rep/week to bronchial tissue}$$

To compare the calculated values with permissible radiation levels used by the National Committee on Radiation Protection in arriving at acceptable environmental levels for radioactive materials, rep values must first be corrected to rem (roentgen equivalent man) units. The committee (*13*) recommends that a factor of 20 be used in making this conversion to compensate for the greater damaging effect of alpha radiation per erg absorbed compared with beta and gamma-radiation on mammalian tissue. Rep values and the corresponding rem values are shown in table IV–1.

TABLE IV–1. *Calculated rep and rem radiation dose per week to human lung and bronchi due to breathing continuously radon and radon daughter products at a radon level of* 1×10^{-11} *curie per liter*

Tissue affected	Average, from inhaled radon		Average, from inhaled radon daughter products	
	Rep per week	Rem per week	Rep per week	Rem per week
Lung	0.000478	0.00956	0.0095	0.19
Bronchi	.000407	.00814	.108	2.16
Bronchi, 1 cm. in diameter	.0046	.092	(1)	(1)

[1] Not calculated.

Alternative figures to those given in table IV–1 can be calculated on the basis of less conservative assumptions. The radiation dose to the lungs can be averaged over a weight of 1,000 grams, the value used by the National Committee on Radiation Protection, rather than the value of 455 grams used in computing table IV–1. The effective depth over which alpha radiation dosage from alpha rays originating in the bronchi should be averaged can be taken as 60 microns rather than 35 microns, used by Evans (*11*), or the value of 40 microns used to compute the dosage to 1 centimeter diameter bronchi shown in table IV–1.

Finally, the National Committee on Radiation Protection is now using ten, rather than twenty, as a factor for converting from rep to rem (*18*). On the basis of these alternative figures the less conservative dosage values as shown in table IV–2 have been calculated.

TABLE IV–2. *A revision of table IV–1 giving, on less conservative assumptions, calculated rep and rem radiation dose per week to human lung and bronchi due to breathing continuously radon and radon daughter products at a radon level of* 1×10^{-11} *curie per liter*

Tissue affected	Average, from inhaled radon		Average, from inhaled radon daughter products	
	Rep per week	Rem per week	Rep per week	Rem per week
Lung	0.00021	0.0021	0.0043	0.043
Bronchi	.00027	.0027	.072	.72
Bronchi, 1 cm. in diameter	.0031	.031	(1)	(1)

[1] Not calculated.

Recently, experimental data have become available bearing directly upon the relative importance of inhaled radon and inhaled radon daughter products in delivering radiation dosage to the lung.

Cohn and his associates (*19*) have measured residual radioactivity in rats, some exposed to radon and daughter products, others exposed to radon from which the daughter products had been carefully filtered. Their results indicate that the radiation dose to the lungs of rats receiving the radon and daughter products is manyfold greater than to the lungs receiving filtered air alone.

Shapiro (*14*) has exposed rats, dogs, and human subjects to radon containing air with various types of dust loads. In the dog experiments, radioactivity of the lungs and tracheae was measured following the exposures, and a calculation made of the radiation exposures they had received. The dog tracheae, about 1 centimeter in internal diameter, correspond in size to the large human bronchi. Extrapolation of these data to the exposure conditions postulated for table IV–1, indicates a weekly exposure of 0.79 rem/week to the lining epithelium of the dog tracheae at a radon level of 1×10^{-11} curie per liter. Averaged for the lung as a whole, it was 0.064 rem per week. These data correspond, in order of magnitude, to the values given in the table and suggest that these calculated values are possibly a reasonable approximation of actual human exposures.

The results derived from both calculation and experiments unite to suggest that most radiation exposure to the lung is due to radon daughter products rather than to radon itself. Experiments supporting this observation have been reported (*20*).

Comment.—Sufficient biologic data are not available to determine finally a maximum permissible concentration for radon daughter products. It is hoped that studies now in progress will furnish these data. In the interim, a working level of 1.3×10^5 Mev of potential alpha energy per liter is suggested for radon daughter products (RaA, RaB, and RaC). This amount of energy will be released by the decay of 100 micromicrocuries of each of these elements through RaC′. On the basis of present information, this level appears to be reasonably safe and not unduly restrictive to mining operations.

SECTION V

Methods of Measuring and Monitoring Radiation Exposure From Radon and Daughter Products of Radon

During the study of the uranium mines, several different methods were used for the determination of radon and radon daughter products, depending on the type of samples to be analyzed, the equipment required, and the degree of precision needed. The methods employed, as well as some other procedures, are described in this section.

PRECISE METHODS FOR MEASURING RADON

The measurement of radon can be carried out in several ways, though all of these depend upon effects of the radioactivity of the element itself and of its daughter products. Most commonly, it is the ionization effects due to alpha particles from radon and its daughters which are measured. However, it is possible to measure the gamma rays or beta particles which arise from the daughter products.

Certain facts and principles are common to all determinations of radon and its daughters. These will need to be discussed before presenting the actual techniques. Table V–1 shows the decay characteristics of radon and its daughters.

TABLE V–1. *Decay characteristics of radon and daughters*

Element	Maximum energy (Mev)	Half life (minutes)	Decay constant, λ (minutes^{-1})
Radon (Rn^{222})	5.5 alpha	5,510	1.26×10^{-4}
Radium A (Po^{218})	6.0 alpha	3.05	0.2270
Radium B (Pb^{214}) [1]	0.65 beta	26.80	0.0259
Radium C (Bi^{214}) [1]	3.15 beta	19.70	0.0352
Radium C' (Po^{214})	7.68 alpha	2.73×10^{-4}	2.54×10^{3}
Radium D (Pb^{210})	0.025 beta	1.16×10^{7}	6×10^{-8}

[1] Principal gamma ray emitter.

Initially, only alpha particles are emitted by pure radon. However, the daughters build up gradually and eventually an increased number of alpha particles are detectable, together with increasing amounts of beta particles and gamma rays. See table V–2. After a few hours, maxima are reached for all of these radiations, and no further build-up of radioactivity is detectable. Thus, for all practical purposes, a state of equilibrium between radon and its daughters is reached.

TABLE V–2. *Growth of radon daughters with decay of initial radon concentration of one micromicrocurie (composite table)*

Time (minutes)	Radon	RaA	RaB [1]	RaC [1]	Total
	Micromicrocuries				
0	1.0000	0	0	0	1.0000
1	.9999	0.2033	0.0028	0	1.2094
2	.9998	.3861	.0068	0	1.2747
3	.9996	.4942	.0206	0	1.5144
4	.9995	.5669	.0341	0	1.6305
5	.9994	.6788	.0488	0	1.7277
10	.9987	.8902	.1416	0.0146	2.0511
20	.9973	.9874	.2281	.0812	2.2943
30	.9962	.9987	.4796	.1783	2.6530
40	.9950	.9984	.5973	.2806	2.8743
50	.9937	.9942	.6846	.3681	3.0606
60	.9925	.9920	.7575	.4912	3.2341
120	.9850	.9855	.9394	.8408	3.7507
180	.9776	.9781	.9721	.9514	3.8792
240	.9703	.9708	.9732	.9709	3.8853
300	.9630	.9634	.9676	.9667	3.8637
360	.9557	.9562	.9608	.9537	3.8264
420	.9485	.9490	.9526	.9368	3.8079
480	.9414	.9419	.9463	.9497	3.7796
540	.9343	.9348	.9393	.9426	3.7509
600	.9273	.9278	.9323	.9355	3.7229

[1] A beta-gamma emitter. Rn, RaA, and RaC' are alpha emitters. Amount RaC' is equal, in curies, to amount RaC.

After this state is reached, the activity decreases because the radon present is gradually decaying. This process is slow relative to the rate of build-up. Actually, the relationships among the various elements are rather complicated and some simplifications have been purposely introduced.

In this consideration of radioactive phenomena, RaD is the logical stopping point in the decay chain because of its long half life. Relative to its precursors, it may be considered stable in terms of hours, days, and weeks. In all further discussions the chain from RaD on is ignored.

It will be seen that, once transient equilibrium has been reached, alpha, beta, or gamma measurements could be utilized for the (indirect) determination of the radon present.

Because of the large and concentrated ionization effects which alpha particles have on gases, they are the most widely used in practice, particularly for very small amounts of radon. Gamma ray measurements also have certain advantages. However, this radiation is not suitable for the measurement of small amounts of radon because gamma ray backgrounds are high and it is the background which determines the feasibility of measuring small amounts of radiation of any kind. Beta counting is less frequently used than either alpha or gamma counting.

Collection of Sample

The environmental radon sample is usually taken in accordance with the procedure followed for a chemically inert gas. A spherical glass flask of one- or two-liter capacity is suitable. Reliable results are obtained by using a flask having two stopcocks and an inlet tube which extends almost to the bottom of the flask. Silicone high vacuum grease is used on the stopcocks.

The air sample is taken by drawing sufficient air through the flask to replace that originally present. The volume of air used for flushing should be at least ten times the volume of the flask. A glass-wool or membrane filter should be attached to the inlet side of the flask to prevent contamination of the flask by radium-bearing dust.

For uranium mine air samples, a one-liter sample is sufficient; for other types of samples, a two-liter sample may be needed. While it is possible to take radon samples directly into the measuring chamber, it is usually found to be more practicable to use the flasks and to avoid transportation of the more delicate chambers.

Various methods have been used to determine the concentration of radon when very low levels are to be measured. Among these, the adsorption on charcoal is probably the most successful and has been used to some extent for this purpose (*3*). However, this method was not indicated in the uranium mine surveys.

Instruments for Measuring Radon

The instruments commonly used for radon measurements that depend upon electrical effects of alpha particles can be divided into two classes according to their mode of operation, namely, (1) those that count electrical pulses and (2) those that measure ionization

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current. While it will be seen later that the two types both depend upon the same general phenomenon, the ionization effect of radiation, their actual operating principles are widely divergent.

Alpha Counting Methods.—The most sensitive general method for determining the radon concentration in a gas involves the pulse counting technique. In such a method, each disintegration produces a pulse, the effect of an individual atom being measured.

An alpha particle possesses relatively enormous specific ionizing power. When it collides with gas molecules, it is able to disrupt certain of the electrical bonds which hold the molecules and atoms together producing positive and negative ions. If left alone, the positive and negative ions will neutralize each other and no electrical effect will be observed.

However, if the ionization process is carried out between two conductors which have a potential difference applied to them, the positive ions will move toward the negative electrode and the negative ions will move toward the positive electrode. Although some of the ions will recombine during their journey, many will reach the electrodes. If the voltage applied to the electrodes is high enough, a rather large proportion of the ions can be collected.

Many of the negative ions are actually electrons; because of their relatively large ratio of charge to mass, they move more rapidly than the heavier positive ions. For this reason, the negative ions are more easily collected in a potential field. Each alpha particle thus creates an electrical pulse.

The intensity and duration of the pulse depend upon a number of variables of which the gas being ionized is one of the more important. It is desirable that the pulses be as intense, or high, as possible and of short duration. The shape of the pulse is also important with reference to the electronic amplifying circuit.

Pulses produced in the presence of oxygen are poorly defined and unsuitable for rapid pulse counting techniques. Thus, oxygen is usually removed from an air sample before it is introduced into the counting chamber. This can be done by passing the air over hot copper turnings, or by adding excess hydrogen and slowly passing the mixture through a vessel containing sponge palladium, causing the hydrogen to unite with the oxygen. This catalyzed reaction proceeds smoothly at room temperature and effectively removes oxygen, leaving an excess of hydrogen which does not interfere with the formation of suitable electrical pulses. Both methods of oxygen removal are in use, but the second method is considerably more convenient in routine work.

For detailed descriptions of various pulse counting devices for gases, reference is made to the literature (*21–25*). Briefly, the steps involved

with the apparatus designed and built by the New York Operations Office of the Atomic Energy Commission may be described as follows.

The apparatus consists of the following units which perform the functions indicated:

1. Preceding the ionization chamber there is a *gas purification train* which includes two palladium sponge units for catalyzing the reaction between oxygen and hydrogen, and a drying agent for removing the water formed by the reaction of hydrogen and oxygen.

2. The *ionization chamber* which has a capacity of about two liters and in which are located two electrodes for the application of the high potential and for transmitting the pulses to the detecting system. The chamber is operated under a pressure of about 6 pounds per square inch gage.

3. A *preamplifier* which is mounted directly over the ionization chamber. This amplifies the very feeble pulses so that they can be transmitted by cable to the main amplifier without being disturbed by extraneous electrical effects.

4. The *amplifier* which receives the signal (pulse) from the preamplifier and amplifies it to the extent that it can eventually operate a relay.

5. The *power supply* which supplies the necessary alternating and direct current voltages for the chamber, various tubes, and relays.

6. The *recording device* which prints an automatic record of the counts on adding machine paper. The interval between prints is adjustable, but a 15-minute interval is commonly used.

Samples are ordinarily received in glass flasks with stopcocks. Hydrogen is added to the sample from a cylinder until a pressure is reached which is about 1.56 times the original pressure. If the flask has a tube extending to the bottom, the hydrogen is added through the tube for better mixing. After allowing about 30 minutes for mixing, the flask is connected to the apparatus, but the stopcock is not yet opened. The valves are turned so that the ionization chamber and the connecting tubing are connected to a vacuum pump. This evacuates the system up to the flask stopcock. The pressure is read by a closed-end manometer after each operation which changes the pressure.

The flask stopcock is now opened and the sample introduced through the purification train into the chamber. When the pressure remains constant the flask is cut off and a mixture of 85 percent nitrogen and 15 percent hydrogen is introduced from a cylinder until a pressure of 6 pounds per square inch gage is attained.

The high voltage is turned on and counting is started immediately to determine whether or not the sample is too high for the apparatus. If it is too high, it is immediately removed to avoid contamination of

the chamber. The counts produced during the first three or four hours are not usually used for calculation purposes. After a sufficient number of counts are recorded the tape is removed and the radon concentration is calculated after applying a correction for the background count.

The formulas for calculating the radon are as follows:

$$\mu\mu c\ Rn/\text{liter (at } P_s,\ T_s) \text{ of sample} = \frac{(\mu\mu c\ Rn \text{ in chamber at } T_c) \times P_s \times P_3}{V_f \times P_{2a} \times (P_3 - P_4)}$$

$$\mu\mu c\ Rn/\text{liter (at } P_s,\ T_s) = \frac{(\mu\mu c\ Rn/\text{liter at } P_s,\ T_c)}{\text{Radon decay factor for period } (T_c - T_s)}$$

$$\mu\mu c\ Rn \text{ in chamber at } T_c = \frac{\text{Counts (corrected for background) per hour at } T_c \text{ for sample}}{\text{Counts per hour for 1 } \mu\mu c \text{ radon}}$$

The significance of the various symbols is as follows:

T_s: Time to which sample is corrected in applying decay factors for radon. It may be the time of transfer to apparatus or any convenient time thereafter.

T_c: Time at which sample was taken; interval $T_c - T_s$ is used in applying decay correction for obtaining radon concentration at sampling time.

P_s: Any pressure at which it is desired to measure the liter of air sample. This would normally be atmospheric pressure at sampling site (P_a), normal atmospheric pressure in the laboratory, or standard pressure (760 mm Hg).

P_{2a}: Pressure of sample in flask prior to adding hydrogen. It will normally be near atmospheric pressure unless a portion of sample has been previously removed.

P_3: Pressure after adding hydrogen; should be about 1.56 times P_{2a}.

P_4: Pressure in flask after sample has been transferred to apparatus chamber.

V_f: Volume of sample flask in liters.

It is seen that the final chamber pressure does not enter into the calculations and neither does the pressure at the sampling site unless the latter is chosen for P_s.

Standardization of the apparatus is accomplished by de-emanation of a radium solution of known radon content. This is done by passing a mixture of 85 percent nitrogen and 15 percent hydrogen through a specially designed bubbler containing radium in 1:19 nitric acid and introducing the purified exit gases into the chamber. This process will be described in more detail later.

Ionization Current Measuring Methods.—The flow of charge between two electrically charged electrodes constitutes an electric current which if large enough can be readily measured. If the radon concentration is sufficiently high, the ionization current becomes steady due to the smoothing out of a large number of random electrical pulses. However, when the concentration is low, an irregular current is obtained and the variation in the current depends upon the design of the electrical detecting system.

With the pulse counting method, an effort is made to obtain sharp and discrete pulses; with the ionization current method, on the other hand, an attempt is made to smooth out or average the pulses into as uniform a current as is practicable.

If the ionization current is passed through a high resistance of from 10^8 to 10^{11} ohms, a potential difference will be developed across the resistor; it is the associated voltage that is measured to secure the ionization current due to radon and its daughters. The detecting instrument must be capable of measuring a fraction of a millivolt produced across a very high impedance if relatively small amounts of radon are involved. Electrical leakages are extremely important with such a device. The classical apparatus used for this purpose is the electrometer, but there are electronic devices available which will do the work more easily.

Such a device is the vibrating-reed electrometer. This apparatus converts the direct current voltage to be measured into an alternating current voltage by means of the vibrating reed. After conversion to alternating current, the voltage is fed through an alternating current amplifier and the amplified alternating current voltage is again converted to direct current for measuring with an ordinary milliammeter or a commercial recorder. This scheme is utilized because small alternating current voltages are much more satisfactorily amplified than are small direct current voltages.

The particular apparatus which will be described was used to analyze the radon samples mentioned in this bulletin. The apparatus was designed and adapted by the New York Operations Office of the Atomic Energy Commission. The amplifier (vibrating-reed electrometer) and the recorder are available commercially, but the chambers and resistance box were designed and added by the Atomic Energy Commission.

The chambers are made of stainless steel and contain a central rod as one electrode. The second electrode is a graphite-coated plastic cylinder which is somewhat smaller than the chamber itself. The electrodes are well insulated.

In use, a 300-volt potential is impressed upon the electrodes by a 300-volt battery; the negative terminal is connected to the cylindrical

electrode. Since the chambers were originally designed for sampling as well as measurement, they were equipped with glass capillary air inlets. These, however, were removed since in this study the air samples were taken in glass flasks and the chambers were used simply as ionization chambers for measuring the radon concentrations. Vacuum gages were also an integral part of the chambers but were used only briefly because of inaccuracies in pointer indications.

The vibrating-reed electrometer and the recorder are commercial instruments with a range of 0 to 1 milliampere; four sensitivity ranges are provided on the electrometer. The vibrating-reed electrometer is remarkably free from maintenance difficulties.

Preceding the amplifier are a resistance box and switch which permit the selection of one of four resistances, namely, 10^8, 10^9, 10^{10}, and 10^{11} ohms. This changes the effective sensitivity of the instrument. There is also a head with a preamplifier and a holder for the ionization chamber preceding the main amplifier.

The actual handling of the air sample is simple. First the chamber is checked for its blank reading and it is evacuated to receive the sample. By means of a T tube, it is connected to a manometer and to the closed sample flask. A tube containing Ascarite® and a drying agent is inserted in the train.

The flask stopcock is opened and the initial pressure (P_1) is read; subsequently when the valve on the chamber is opened, the sample flows in, and the resulting pressure (P_2) is observed.

After closing the stopcock and valve, the chamber is removed and room air is admitted by opening the inlet valve. After standing for about four hours to allow for the build-up of daughters, the chamber is placed on the instrument and the average reading of the meter is taken or a recording is made. If the sample is low, a correction is made for the blank reading of the chamber, but this correction is usually insignificant for uranium mine air samples.

The radon concentration is calculated from the following formula:

$$\mu\mu c\ Rn/\text{liter (at } T_c, P_c) = \frac{M_v \times C.F. \times P_c}{R \times F_c \times V_c \times P_1}$$

The significance of the symbols is as follows:

T_c: Time to which the correction is to be made.

P_c: Any pressure at which it is desired to measure the liter of air sample. (P_1 is the pressure of sample in flask, but does not enter into the calculations unless it is desired that $P_c = P_1$)

M_v: Millivolts read from the instrument, or meter reading times sensitivity setting.

C. F.: Calibration factor for chambers which is obtained by measuring a known amount of radon in chamber. (See following discussion

on calibration.) Its numerical value is approximately 8.3×10^{11} micro-microcuries per milliampere and it includes variations among the chambers and among the 10^8, 10^9, 10^{10}, and 10^{11} voltage-developing resistors.

R: Resistance in ohms over which developed voltage is measured.

F_d: Fraction of original radon activity remaining at time of measurement.

V_c: Volume of ionization chamber in liters.

P_b: Pressure in chamber before admitting room air.

Calibration of Radon Measuring Devices

Calibration of radon measuring instruments was carried out in two different ways. These were both accomplished by de-emanation of radium solutions containing calculated amounts of radon.

Sealed Tube Method.—A known amount of radium in dilute hydrochloric acid solution (about 1 ml) is sealed in a small glass tube and is allowed to stand for a month so that the equilibrium amount of radon is present. If the solution cannot be sealed that far in advance, the tube can be boiled out just before sealing and this time used as the zero time in calculating the radon content.

The tube is placed in a slightly larger piece of copper tubing which is attached to a purification train which removes acid and water vapors. The train, in turn, is connected with the evacuated ionization chamber or other sample inlet of the apparatus.

The glass tube is crushed with pliers and a small flame is applied to the copper tubing to boil out the liquid. Finally, the heat is raised to well above the boiling point of the liquid to insure its complete vaporization. A gentle stream of air, or counting gas, is admitted intermittently during the boiling process to flush the radon through the purification train.

The known amount of radon thus introduced is run as a sample. After appropriate corrections for the decay of radon, the calibration factor for use in the formula is calculated.

This method of calibration was essentially that used by the New York Operations Office of the Atomic Energy Commission, from whom it was obtained. While the method is accurate, it is at times relatively troublesome to carry out.

Bubbler Method.—A calibration method based on that described by Shandley (*24*) is extremely simple to carry out and, once the apparatus is made and filled, it is as simple to calibrate the apparatus as it is to run a sample.

The importance of Shandley's method of calibration rests on the fact that radon can be quantitatively removed from a clear, cold 5:95

nitric acid solution of radium by the technique described in his paper. Air is bubbled slowly through the radium solution into an evacuated flask. The radon is transferred from the flask to the apparatus in the same way that a sample is done. The bubbling is performed in a column which has a medium fritted glass disc at the bottom, and a capillary is used to restrict the air flow so that the de-emanation requires 20 minutes.

In this laboratory, a more convenient variation of Shandley's apparatus was designed. See figure V-1. The smaller device is used for standards and has to be filled through the hole in the stopcock barrel before assembling the stopcock. After experience with this device, the larger one was designed primarily for use with samples. It includes an opening for filling, a back-up bubble trap on the gas inlet tube, and spherical joints for attaching to apparatus. The simpler devices are satisfactory if properly used.

The de-emanating gas is admitted through the side tube and the exit tube is connected through a purifying train (a glass tube filled with suitable chemicals) and a capillary to the apparatus or chamber to be calibrated. If the radium concentration is to be low, the apparent radium content of the bubbler and the 3.93 nitric acid should be determined and taken into account. The apparatus and method have proved satisfactory for the calibration of the ionization current measuring and of the pulse counting types of instruments.

Fragmentary data indicate that the efficiency of de-emanation depends more upon the ratio of the volume of liquid to the volume of flushing gas than it does upon the ratio of the volume of flushing gas to the volume of the gas space. This statement is based upon the assumption that the gas space above the liquid has a volume of no more than a tenth of the volume of the liquid. Experiment indicates that about 99 percent of the radon is removed in the first 5 minutes of de-emanation when the liquid volume was about one-fourth of that of the flushing gas. On the other hand, another experiment showed that a volume of flushing gas approximately equal to the liquid volume (gas space volume was about 5 ml) removed only 98 percent of the radon.

Accuracy of Methods

The accuracy of the two methods varies considerably with such factors as the amount of radon present, the background, the duration of the run, and the care exercised in transferring the sample. Work by Shandley (24) with known amounts of radon indicates deviations in the range of 0.7 to 1 percent when working with 2.6 to 40 micro-

nitric acid solution of radium by the technique described in his paper. Air is bubbled slowly through the radium solution into an evacuated flask. The radon is transferred from the flask to the apparatus in the same way that a sample is done. The bubbling is performed in a column which has a medium fritted glass disc at the bottom, and a capillary is used to restrict the air flow so that the de-emanation requires 20 minutes.

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Accuracy of Methods

The accuracy of the two methods varies considerably with such factors as the amount of radon present, the background, the duration of the run, and the care exercised in transferring the sample. Work by Shandley (*24*) with known amounts of radon indicates deviations in the range of 0.7 to 1 percent when working with 2.6 to 40 micro-

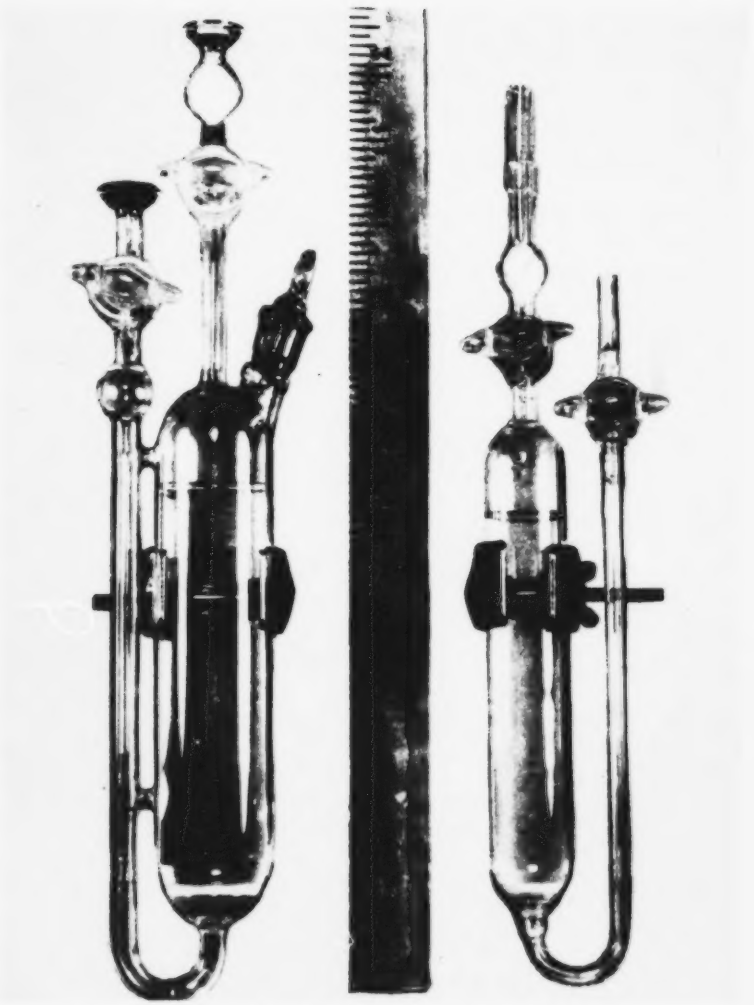


FIGURE V 1. — *Apparatus used in bubbler method for calibration of radon measuring devices.*

microcuries of radon in a pulse counting type of apparatus. Reference should be made to the paper by Curtiss and Davis (*22*) for statistical considerations applying to the relation between background and the concentration of radon being determined.

TABLE V–3. *Radon recovered with use of ionization current method*

Radon taken	Radon found	Percent recovered	Difference between percent recovered and 100 percent
Micromicrocuries			
4,020	4,010	99.7	−0.3
862	870	100.9	0.9
158	157	99.4	−0.6
95.5	99.5	104.2	4.2
33.9	35.2	103.8	3.8
33.1	30.3	91.5	−8.5
14.3	14.1	98.6	−1.4
14.2	13.0	91.5	−8.5
11.0	11.2	101.8	1.8
4.3	4.6	106.9	6.9

Table V–3 summarizes data collected in this laboratory with the use of the ionization current method. The variations from the theoretical figure include errors due to variation in chamber calibrations, since such calibrations had not been made at the time the data were taken. With regard to the lower concentrations, chambers were used which had been specially selected for low backgrounds, so that the results as obtained could not be expected on routine samples. These particular known samples were de-emanated into sample flasks and, thus, represent the recoveries which can be expected from the operations performed in the laboratory. In this connection it must be stated that leakage of samples in transit from the mines is sometimes a serious problem, as shown by certain obviously low samples in table VI–21 (TN–1, S–12, S–20).

Calibration data on the chambers indicated that about 10 percent of them deviated approximately 4 percent (in the same direction) from the mean, while 75 percent of them deviated no more than 1 percent.

While the methods of determining radon can be precise, on a routine basis the results are probably correct to within 5 percent assuming that no leakage of the sample took place prior to its receipt in the laboratory. No temperature correction for the samples was normally made, because the temperatures at the sampling sites were not taken.

FIELD METHOD FOR MEASURING RADON

A radon scintillation cell has been described by Van Dilla and Taysum (*26*). This device consists of a 125 milliliter cell, coated on the inside with a zinc sulfide phosphor. In use, the cell is evacuated and a sample of the air to be tested is drawn into it. After equilibrium is reached, the scintillations are counted using any standard photomultiplier tube and scaler combination. A modification of this method employs flush-through cells instead of evacuated flasks.

While this method requires a vacuum pump, cells, scintillation counter, and an electrical supply, its use is possible in the field for the rapid determination of radon. Some of the work reported in section VI was done by this procedure. It is reliable for the analysis of samples containing at least 50 micromicrocuries of radon per liter.

METHODS FOR MEASURING RADON DAUGHTER PRODUCTS

Since the radiation dose to the respiratory system was shown in section IV to be largely due to the daughter products of radon which are retained in the lungs, it was necessary to develop methods for measuring the amounts of these elements present in mine atmospheres to evaluate the health hazard which they create. The basic principles of such methods will be presented with some details of the adopted field procedures.

Basic Principles

Radon daughter products of a mine atmosphere can be sampled by drawing known quantities of mine air through a filter paper. Molecular filters appear best adapted to this purpose because of their high retentivity for small dust particles and because these dust particles are deposited on or close to the front surface, reducing or eliminating the need for corrections for filter absorption during subsequent measurement of radioactivity (*27*). Hand-operated air pumps have been developed suitable for this purpose (*15*).

For the measurement of the radioactivity, samples are usually taken from the mine to a nonradioactive area. Measurements can be made by *alpha* counting, using a flow proportional counter, an alpha sensitive field instrument, or an alpha scintillation counter; measurements can also be made by measuring *gamma* radiation with the use of a well-type scintillation counter similar to the one designed by Anger (*28*).

By using suitable permanent radioactive standards, experimental counting rates for the collected samples can be transformed to absolute radioactive disintegration rates. Care must be taken that the measuring apparatus has the same sensitivity, or at least a constant fraction of the same sensitivity, for the standard that it has for the unknown samples being measured. Some common alpha standards, for example electroplated uranium, produce alpha rays with lower energies than those from radon daughter products. A few microcuries of radium or ore containing radium sealed in a container that can be measured with the same geometry as filter paper samples make a good standard for gamma ray measurements.

Radioactive measurements of radon daughters in dust samples can be corrected for the radioactive decay from the time of sampling to the time of measurement with the use of appropriate graphs or tables. Figure V–2 shows such a graph of decay for alpha activity.

The curve shown in figure V–2 can be used to compute the initial alpha activity of radon daughters in equilibrium in an atmosphere that produced a measured radioactivity on a filter paper sample of this atmosphere at a later time.

Assume, for example, that 35 minutes after an instantaneous filter paper sample was taken of the radon daughter products of such an atmosphere, the filter paper showed a radioactivity corresponding to an over-all emission after correcting to 100 percent geometry and no self-absorption of 50 alpha particles per minute. From the curve in figure V–2 alpha activity at 35 minutes is seen to be 37 percent of alpha activity at time zero. The initial alpha activity rate was therefore 135 disintegrations per minute, half due to RaA and half due to RaC′.

In actual practice, samples cannot be taken instantaneously nor are the daughters always in equilibrium with each other. However, it so happens that when an alpha measurement is made at approximately one hour after the sample is collected and is corrected to the sampling time with the use of the curve in figure V–2, the actual alpha energy released by the radioactive decay of this sample will be within 20 percent of the energy release calculated on the basis of an initial radioactive equilibrium of radon daughters. Moreover, if the actual sample collection takes no more than 10 minutes and zero time is taken as the mid-time of the collection period, the error due to the fact that the dust sample collection is not instantaneous will not exceed 10 percent.

The reasons that the total alpha ray dose released by a collected sample as estimated by the alpha activity one hour after collection is nearly independent of the initial state of equilibrium of RaA, RaB, and RaC may be illustrated by the following calculations.

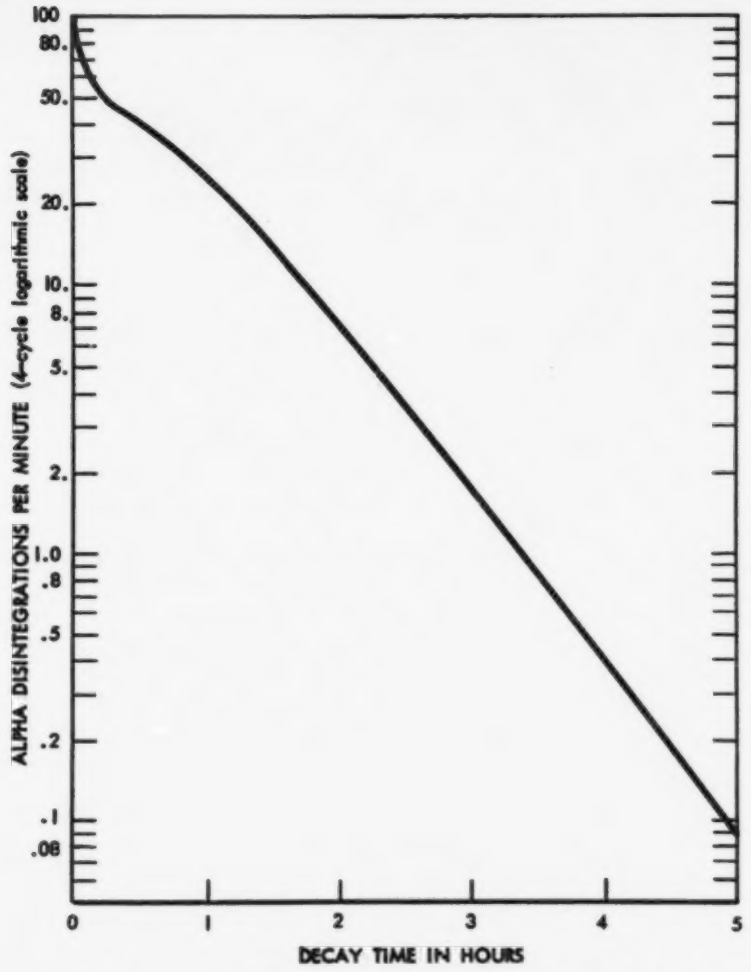


FIGURE V–2.—*Decrease with time of alpha particle emission of radon daughters, RaA through RaC', separated from radon and in radioactive equilibrium with each other at time zero, with an initial alpha activity of 100 disintegrations per minute, half due to RaA and half to RaC'.*

From figure V–3, based on calculations reported by Shapiro (*14*) an amount of RaA alone which was initially decaying at a rate of 10 disintegrations per minute would at the end of one hour have as a residuum alpha emitters, largely RaC′, decaying at the rate of 0.41 alpha particle per minute.

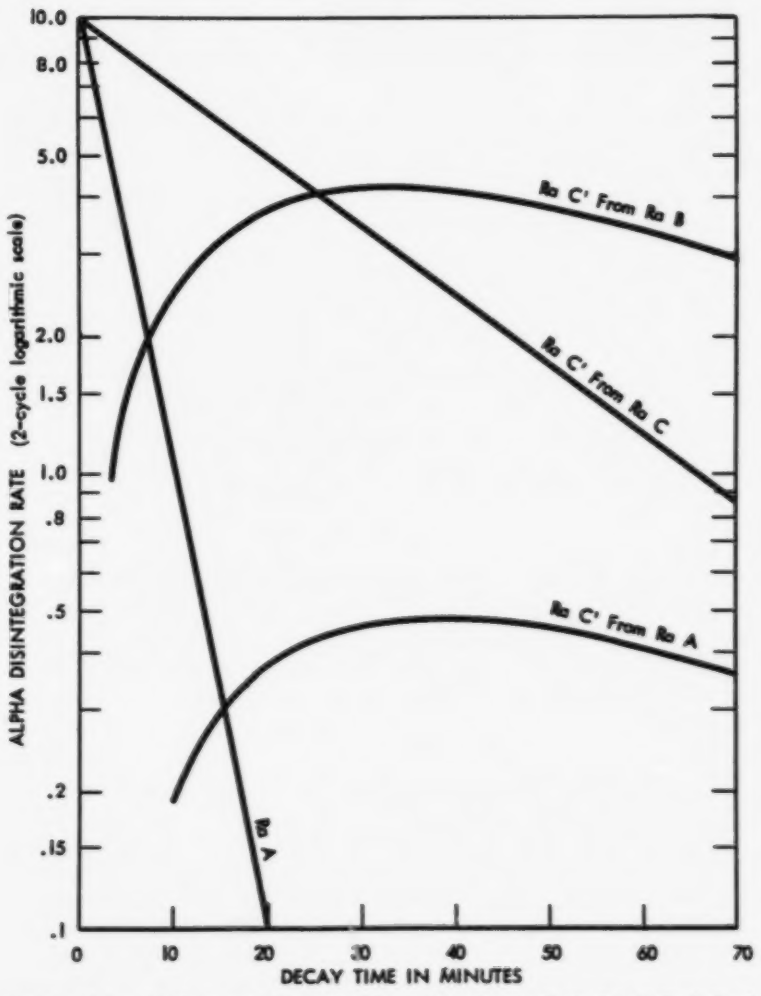


FIGURE V-3.—*Build-up and decay of alpha activity from individual initially isolated radon daughter isotopes, RaA through RaC, with an initial disintegration rate for each isolated isotope of 10 disintegrations per minute.*

In a similar manner RaB, initially present in an amount decaying at a rate of 10 beta particles per minute, would at the end of one hour give rise to 3.42 alpha particles per minute, again as RaC′.

RaC initially present in an amount decaying at a rate of 10 disintegrations per minute will, at the end of one hour, be represented as RaC′ decaying with 1.20 alpha particle emissions per minute.

For any radioactive isotope, the total number of atoms present is $\frac{\text{disintegrations/unit of time} \times \text{half life.}}{0.693}$ For amounts of radon daughter products, each decaying at a rate of 10 disintegrations per minute, the numbers of parent atoms initially present are: for RaA, 43.8; for RaB, 386; and for RaC, 284.

The total amount of alpha energy released by the complete decay of these atoms through RaC′ will be:

For RaA, $43.8 \times 13.7 = 601$ Mev
For RaB, $386 \times 7.7 = 2972$ Mev
For RaC, $284 \times 7.7 = 2187$ Mev

The sum of alpha energies released is thus 5760 Mev; the sum of alpha decay rates at one hour is 5.03 alpha disintegrations per minute, and the total alpha energy for complete decay corresponding to one alpha disintegration per minute, one hour after a sample collection, for which RaA, RaB, and RaC are in equilibriu is:

$$5880/5.03 = 1145 \text{ Mev}$$

The most extreme case for nonequilibrium of RaA, RaB, and RaC is the one where in the atmosphere only the 3.05-minute half-life RaA is present, RaB, and RaC assumed to be completely absent. In this instance the alpha energy for complete decay corresponding to one alpha disintegration per minute, one hour later is:

$$601/0.412 = 1459 \text{ Mev}$$

One notes that this figure is higher than the equilibrium figure by a factor of only 1459/1145 or 1.274.

It seems likely that the hazard from inhaling into the human lung a mixture of radon daughter products also will correspond reasonably closely to the total alpha energy released by the decay of these radioactive materials. On this supposition then, if the inhalation hazard had been based upon an assumption of radioactive equilibrium of RaA, RaB, and RaC for the atmosphere sampled and in fact only RaA were present, the actual hazard would have been 27 percent greater than estimated. This possible error is small compared with other uncertainties in estimating the human hazard from breathing radon and radon daughter products.

Further calculations show that if an atmosphere initially contained RaA, RaB, and RaC in the ratio, 100:50:50, the energy released is underestimated by 2 percent; if the ratio is 100:50:25, then energy released is overestimated by 7 percent; if the ratio is 100:50:0, the energy released is overestimated by 17 percent.

If the measurement is made two hours after the sample is collected, and the initial ratio is assumed to be 100:100:100 where in fact it was 100:0:0, the actual alpha energy is underestimated by only 4 percent.

Figure V–4 shows the initial level of radon daughter products in equilibrium that corresponds to one alpha disintegration per minute measured at a time shown on the abscissa following the rapid or "grab" collection of a radon daughter sample. It can be considered

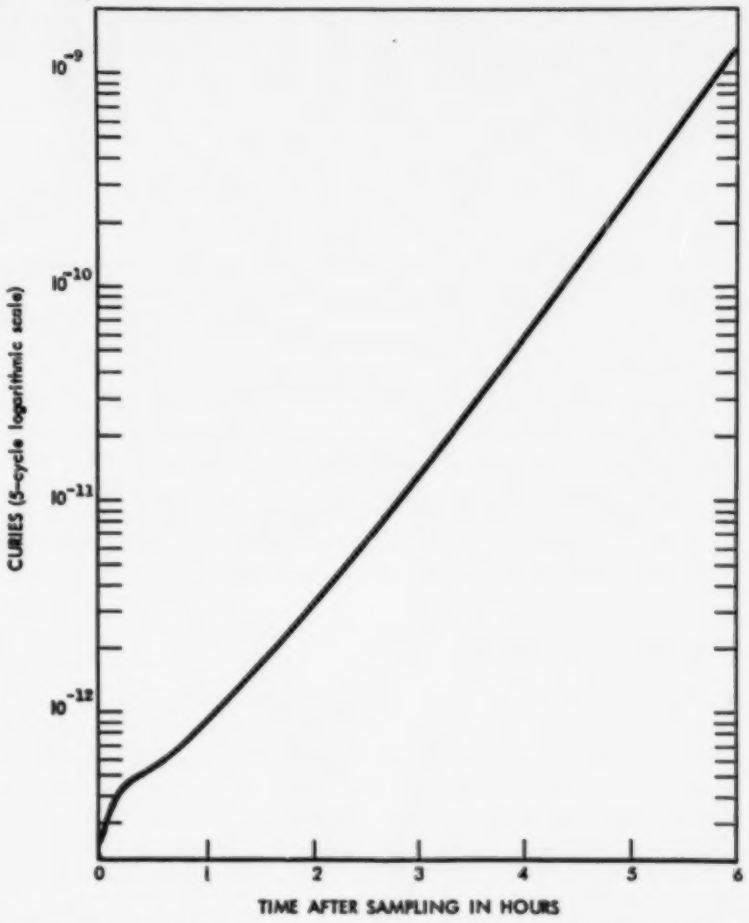


FIGURE V–4.—*Initial level of individual radon daughter products, RaA through RaC', in equilibrium, that results in one alpha disintegration per minute at time shown on horizontal axis. The curve meets the vertical axis at approximately* 2.3×10^{-12}.

a calibration curve relating the measured alpha activity of a collected sample of radon daughter products to the effective initial level of radon decay products in air at the time the sample was taken.

For example, assume that the daughter products are collected from a 50-liter portion of air over a 5-minute-period, the mid-point of which was 65 minutes before the mid-point of an alpha activity measurement of the collected sample. Assume further that the measurement showed 780 counts per minute and that the alpha-measuring efficiency was 38 percent.

From figure V–4 one disintegration per minute measured at this time corresponds to 1×10^{-13} curie of radon daughter products in equilibrium with each other. The calculated initial effective radioactivity due to decay products of the atmosphere from which the experimental sample was taken is therefore:

$$\frac{780}{50} \times \frac{1 \times 10^{-13}}{0.38} = 4.04 \times 10^{-11} \text{ curie/liter}$$

Irrespective of the actual distribution of daughter product activity among RaA, RaB, and RaC, the human hazard would be approximately the same as that from breathing daughter products in equilibrium at a level of each daughter product, RaA through RaC′, of 4.04×10^{-11} curie per liter.

Actual experimental radioactive decay curves of the daughter products from various radon-containing mine atmospheres have been published (*15*). Graphs and tables of radioactive decay rates under various assumed conditions have also appeared (*14*, *29*). These data are useful, for example, in making similar calibration curves where it is proposed to measure daughter products with beta or gamma rather than with alpha ray measuring apparatus.

Original Field Method

Ideally, a field method for measuring atmospheric concentrations of radon daughters would have the sensitivity and accuracy of laboratory methods and would use rugged equipment that could be transported readily. However, since uranium mines in the Colorado Plateau are isolated and usually do not have electricity available, it was necessary to develop a procedure that would be reliable and would still give results that would have sufficient accuracy for the purposes of the study.

The method adopted was based upon a study (*30*) of the build-up and decay of equilibrium mixtures of RaA, RaB, RaC, and RaC′ as they were collected on filter paper and of the decay of the collected

daughters after sampling was stopped. This method gave the alpha activity of the collected particulate matter in a measured volume of air, which was then calculated to RaA plus RaC′ assuming that radioactive equilibrium existed among all the daughters of radon.

As pointed out in the first part of this section, the accuracy of such methods is sufficient for control work, and the simplicity and reliability of the equipment made it a very useful procedure. All of the data reported in section II were obtained by this method. The field method follows.

Air is drawn through Whatman 41 (one-inch in diameter) or membrane filter paper at a measured rate (14–23 liters per minute) by a hand-cranked pump, or other suitable air-moving device, for either a 5- or 10-minute period. To simplify calculation tables were prepared for these two sampling intervals. See table V–4.

TABLE V–4. *Correction of observed number of disintegrations per minute to number at time zero*

Time from end of sampling in minutes	Correction factor		Time from end of sampling in minutes	Correction factor	
	5-minute sample	10-minute sample		5-minute sample	10-minute sample
20	1.60	1.55	75	4.7	3.9
25	1.80	1.65	80	5.2	4.4
30	2.10	1.80	85	5.8	4.8
			90	6.5	5.3
35	2.27	1.90			
40	2.45	2.05	95	7.2	6.0
45	2.65	2.20	100	8.0	6.5
50	2.90	2.40	105	9.0	7.2
55	3.17	2.65	110	10.0	8.0
60	3.50	2.95	115	11.5	8.8
			120	13.5	9.8
65	3.8	3.2	125	14.0	11.0
70	4.3	3.5			

The filter paper is removed from the mine and the alpha activity on the paper is measured by a field instrument (a Juno-type device is satisfactory for this purpose) which has been cross-calibrated against a laboratory counter using an RaC′ source [1] so that the scale readings can be converted to alpha disintegrations per minute (dpm). To prevent contamination, the instrument is not taken into the mines.

The activity (dpm) obtained by reading the instrument is converted to time zero by a factor obtained from the correction table. This value is substituted in one of the following equations:

[1] Uranium ore in a closed container is a good source of radon daughters. Samples taken on filter paper should be allowed to stand for 15 minutes so that essentially all RaA will decay and only alpha particles from RaC′ will be measured.

388370—57——4

$$\mu\mu c/l \text{ of RaA+RaC}' = \frac{0.112\ (dpm)}{v} \text{ for 5-minute sample}$$

$$\mu\mu c/l \text{ of RaA+RaC}' = \frac{0.066\ (dpm)}{v} \text{ for 10-minute sample}$$

where, *dpm*: alpha disintegrations per minute at time zero, and
v: sampling rate in liters per minute.

Recommended Field Method

As previously pointed out, the original field method gives results that are probably not seriously in error with regard to alpha energy released. However, the method is not accurate for expressing the results as micromicrocuries per liter of any isotopic species if secular equilibrium does not exist among the immediate daughters of radon. For non-equilibrium conditions, the figures obtained by calculating from alpha disintegrations per minute to micromicrocuries per liter are only *apparent* concentrations which may be misinterpreted as real concentrations.

Maximum permissible levels for radon and radon daughters have usually been expressed in terms of activity as micromicrocuries per liter or microcuries per milliliter, such as "radon plus daughters, 10^{-7} microcuries per ml" (*18*). This procedure has been followed even though it is now recognized that the radiation dose from the radon alone in mixtures with its daughter products is relatively unimportant. See section IV.

Such statements must be clearly defined to avoid confusion and, at best, refer to theoretical conditions which are rarely encountered in practice. However, if atmospheric concentrations of daughter products are expressed in terms of total alpha energy released, ambiguity is avoided, and it becomes unnecessary to attempt to determine the amounts of RaA, RaB and RaC present, a procedure which cannot be performed routinely in the field.

Such a method of calculation which measures alpha disintegrations per minute on a filter paper sample will give figures representing the potential alpha inhalation hazard and can be related directly to any reference level.

If 100 micromicrocuries each of RaA, RaB, and RaC per liter are taken as a suggested working level, it can be calculated from the data given in the earlier discussion of basic principles that the alpha energy released by the decay of one liter of this mixture through RaC′ is 1.3×10^4 Mev. Such a mixture would give 112.6 disintegrations per minute on a filter paper one hour after collection. Therefore, a meter reading showing 113 disintegrations per minute at 60 minutes will represent 1.3×10^4 Mev per liter of alpha energy.

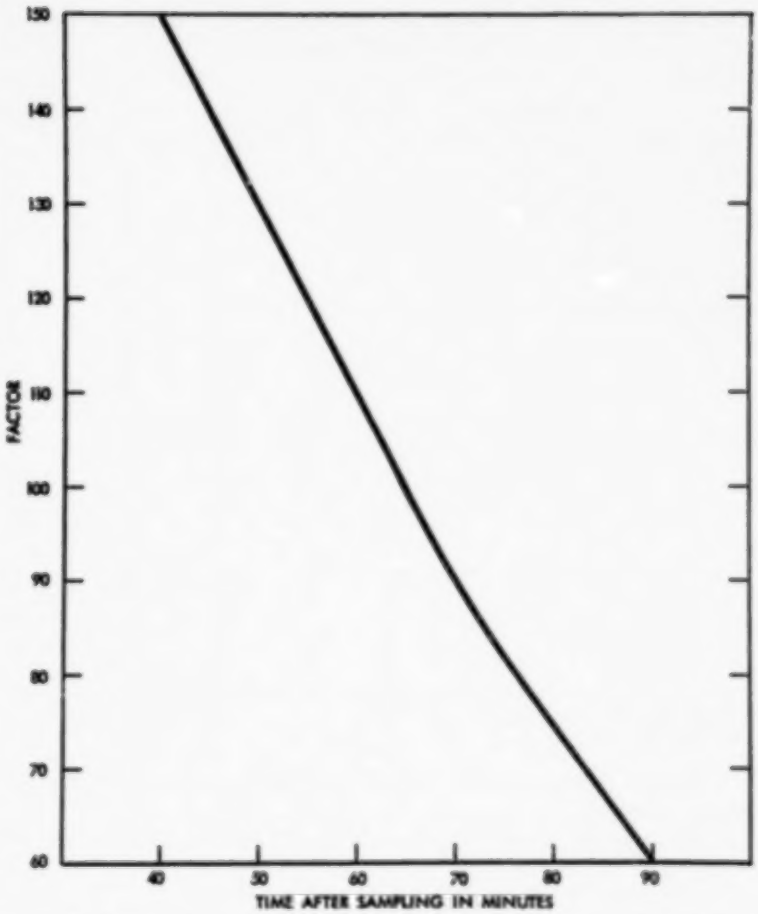


FIGURE V–5.—*Factor-time relationship for determining percentage of working level of radon daughter products in atmosphere. Reference working level: 1.3×10⁵ Mev. (Based on Kusnetz (31), fig. 1, p. 87.)*

A modification of the original field method based on these principles has been described (*31*) and is summarized below. In this procedure, factors for calculating from alpha dpm to Mev/l were determined by solving Bateman-type equations for the decay of various equilibrium and nonequilibrium mixtures. These factors are given in figure V–5, and the errors in estimating the alpha energy per liter are listed in table V–5. The method is as follows:

TABLE V–5. *Percent error of working level estimation with adjusted factors for different times and equilibrium ratios*

Equilibrium ratio	Time after sampling in minutes	Factor	Percent error
1:1:1	40	100	7
	50	100	5
	60	110	3
	70	90	5
	80	75	7
	90	60	2
1:0.9:0.8	40	100	8
	50	100	4
	60	110	3
	70	90	12
	80	75	10
	90	60	4
1:0.43:0.25	40	100	2
	50	100	2
	60	110	3
	70	90	4
	80	75	11
	90	60	6
1:0.12:0.06	40	100	[1]7
	50	100	[1]7
	60	110	[1]3
	70	90	3
	80	75	13
	90	60	7

[1] Percent underestimated.
Source: Kusnetz (31), p. 47.

1. Collect a measured air sample on filter paper as given in the original method.
2. Measure the alpha dpm from 40 to 90 minutes after the end of sampling.
3. Calculate the alpha dpm per liter of air sampled.
4. Divide the dpm per liter by the factor from figure V–5.
5. The resultant figure gives the multiple or fraction of the suggested working level (1.3×10^5 Mev/l) existing in the air. Multiply this figure by 1.3×10^5 to determine the amount of potential alpha energy in Mev per liter of air.

MEASUREMENT OF INDIVIDUAL CUMULATIVE EXPOSURE

Knowledge of radon and radon daughter product concentrations in the working areas of mines and establishments where uranium ores are processed is of medical importance only to the extent to which it

can be used to establish presumptive radiation exposure of workers in such areas.

Polonium in Urine

It is possible that a type of measurement made on exposed individuals themselves will give a relative measurement of their integrated exposure to radon and radon daughters over the past few months or years. This measurement is the concentration of polonium in the urine of these individuals. The validity and usefulness of this type of measurement need further exploration.

As shown in figure III–1 and table III–1, radon decays rapidly through its daughters to radiolead, Pb^{210}, a beta-emitting isotope with a half life of 22 years.

Current experimental data (*32*) indicate that when radon daughters are deposited in the lungs the decay to radiolead occurs largely in the lungs themselves. Radon itself is distributed chiefly in the fat depots of the body and decay of radon to radiolead probably occurs largely in these sites. From studies of lead itself deposited in the lungs, it is believed that a substantial portion of this lead is transported and deposited in the bones where it remains for long periods of time; probably radiolead derived from radon and its daughters behaves similarly.

Radiolead decays through RaE, a beta-emitting isotope of bismuth, to RaF or Po^{210}, an alpha emitter with a half life of 138 days. The metabolism of this polonium isotope has been extensively studied in human subjects and experimental animals (*33*). It is known that intravenously administered polonium is deposited largely in the soft tissues of the body and excreted slowly in the feces and urine. The biologic half life of Po^{210} stored after intravenous injection in the human body is about 57 days, and about 0.13 percent of the body burden is excreted in the urine daily. Nothing is known about the rate of excretion of polonium derived from radiolead stored in bony tissues. Presumably a portion of this polonium is also excreted.

The polonium content has been measured of urine specimens obtained from uranium miners of the Colorado Plateau area, and from control human subjects with no known radon exposure (*34*). It was demonstrated that indeed the polonium content of miner's urine was great enough to be easily and quantitatively measurable and many times higher than that found for any control subjects. The potential feasibility of this monitoring method is thus demonstrated.

The usefulness of this monitoring method will depend upon yet undetermined facts regarding the constancy with time of polonium

excretion following a specific dosage from radon and radon daughters. If it is found that polonium excretion does not change by a factor of more than three to five for long periods following radon exposure, it follows that such measurements may be useful in determining a value approaching the integrated dosage received by individuals over a period of many years. In particular, it may be possible to determine whether radon exposure shows a correlation with any types of illness or disability suspected of having been caused by this type of radioactive exposure. If it is found that polonium excretion, following a given radon exposure, decreases rapidly over a period of years, the use of polonium urine values may be more strictly limited to determining integrated exposure values over a period of weeks or months.

This type of measurement may be of further usefulness since it may provide a more direct demonstration of the safety, or possibly the hazard, of an individual's working conditions, than infrequent spot measurements of the workplace. In particular, it may be more feasible to develop a method for periodic collection and assay of urine samples than to develop a routine method for adequate monitoring of small mining operations by air and dust sampling.

It will probably be worthwhile, therefore, further to study the assay of polonium in urine as a measure of radon and radon daughter product exposure. Particular emphasis will need to be placed upon the establishment of the degree to which a correlation exists between exposure and the magnitude of polonium excretion, and upon the rate with which polonium excretion decreases with time following the cessation of radon exposure. The method used for routine urine collection must be such that contamination of the specimen by external radioactivity is negligible.

SECTION VI

Control of Radioactive Dust and Gas in Underground Mines

Theoretical studies and some experimental work on the effect of ventilation have been reported and showed that (1) relatively small amounts of fresh air reduce the atmospheric concentrations of radon and its daughter products by large factors, and (2) radon daughter products can be efficiently removed from mine atmospheres by filtration, lowering the levels of these elements to ultimate limits which depend on the ambient radon concentration (*35*, *36*).

The object of this section is the presentation of information necessary for the formulation of recommendations for ventilation. The Atomic Energy Commission supported the studies furnishing this information and some of the observations appearing here were originally presented elsewhere (*37*, *38*).

Specifically, the purpose of the studies was, (1) to determine the amount of ventilation necessary to reduce concentrations of radon and its daughter products to reasonable values in presently operating uranium mines, (2) to determine the effectiveness of method of delivery of the ventilation on reductions observed, and (3) to develop some simple method of estimating the quantity of air necessary to control radioactive gas and dust in any particular portion of a mine, and to consider general mine ventilation requirements.

Throughout, the suggested working level for air-borne radon daughter products has been taken as 1.3×10^5 Mev of alpha energy per liter, the amount that would be released by the decay of 100 micromicrocuries of RaA plus 100 micromicrocuries of RaB plus 100 micromicrocuries of RaC to RaD.

EQUIPMENT

All degradation products were collected by drawing air through membrane filters by means of a hand-cranked vacuum pump. Alpha counting of daughter products was done with a methane-flow proportional counter, using a stopwatch for timing. Power was obtained from a 500-watt motor generator.

Radon was determined by the ionization chamber-vibrating reed electrometer method developed by the New York Operations Office

of the Atomic Energy Commission. A phosphor-coated chamber method (*26*) was used for some of the last samples. Samples for the vibrating reed electrometer were taken in one- or two-liter, two-stopcock flasks and shipped to our laboratory in Salt Lake City. Other samples were taken directly in the phosphor-coated chambers and counted in the field by use of a photomultiplier tube (RCA 5819) and decimal scaler.

Ventilation was initially accomplished by means of an Ilg BC–40 belted fan and flexible vent tubing. The Ilg fan proved to have characteristics not too suitable for this type of ventilation, and was replaced by a Buffalo No. 3 steel plate exhauster-type blower for the latter part of the study. Both fans were belt-driven by a one-cylinder gasoline engine mounted, as was the fan, in the bed of a ½-ton truck.

Ventilation measurements were made with a velometer, Hastings portable air meter, or vane anemometer. Qualitative tests were made with a smoke tube. Measurements of mechanical ventilation were accurate to within plus or minus 10 percent. Natural air movements were too low to be measured quantitatively.

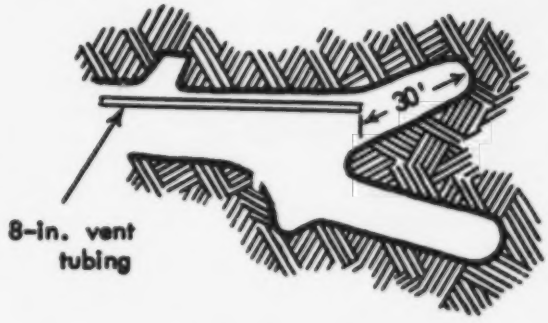
METHOD

Since the radon daughter samples required immediate counting, and portable equipment permitted the handling of only one sample at a time, the number of samples which could be taken was severely limited. For this reason, sampling was restricted to representative locations. Since the major portion of a miner's time is spent at or near the working face, this location was invariably included. Samples were also taken at various other locations, such as toward the portal in the return air stream to gain some information as to exposures of mining personnel while tramming and operating inside hoists.

In each case, a sample was taken before ventilation was started to determine the concentrations of the various radioisotopes under conditions of natural ventilation. While this sample was being counted, the ventilation tubing was put into place and connected, and the blower turned on.

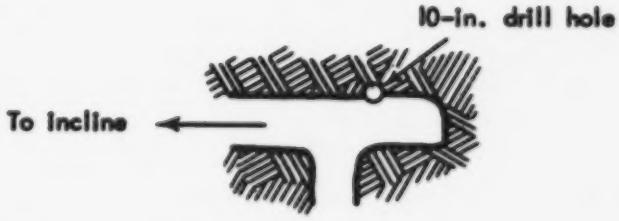
Ordinarily, a minimum of two hours of ventilation was allowed before further samples were taken, so that concentrations might approach a steady state. Ventilation rates were measured at the discharge from the flexible ventilation tubing with an anemometer, velometer, or the Hastings air meter. Sketches of the areas under study appear as figures VI–1 and VI–2.

(1)



Samples NH-1 through NH-3;
NH-101 through NH-105; NH-107

(2)



Samples TN-1 and TN-2

FIGURES VI-1, 2.—*(1) Ventilation and sampling locations for Samples NH-1 through NH-3, NH-101 through NH-105, and NH-107. (2) Sampling point and drill hole for Samples TN-1 and TN-2.*

Radon samples were taken by drawing mine air through specially encased one- or two-liter, two-stopcock flasks, similar in design to those used by the U. S. Bureau of Standards. A field trip was made in January 1954 to survey winter mine conditions. Equipment was available for field analysis of radon. Samples for this purpose were taken in 120 ml, phosphor-coated, evacuated glass chambers, and subsequently counted by a photomultiplier and scaling unit.

Radon daughter samples were taken on 1-inch diameter membrane filters, using a holder which gave ¾-inch diameter open to the air. Because electricity was not available, a hand-crank pump was used as a source of vacuum. With the use of timed cranking, the variation in sampling rate was ordinarily kept to within plus or minus 5 percent.

Radon daughter samples were removed from the mine as expeditiously as possible, since it was attempted to get an alpha count on the samples within 5 minutes after completion of sampling.

An alpha decay curve for the first 45 minutes after sampling was obtained, and the concentrations of the various radon daughter products were determined, as earlier described (*15*).

The total potential alpha energy in million electron volts per liter was calculated from the amount of each isotopic species present.

Since the method of determining individual isotopes by decay curve analysis is relatively sensitive, the RaA concentration may be in error from 10 to 20 percent. The calculated RaB and RaC concentrations are less influenced by errors, however. Thus the total alpha energy concentration is probably accurate to within plus or minus 5 percent.

RESULTS

Mechanical Ventilation

Reference is made to the results of experiments conducted in dead-end drifts, small rooms, stopes, and large rooms.

Samples NH–1 through NH–3. This series of samples was taken in a uranium mine with rather large ore bodies; see table VI–1. A satisfac-

TABLE VI–1. *Effect of ventilation on concentration of radon and radon daughters*[1]

[Samples NH–1 through NH–3]

Sample number	Radon ($\mu\mu c/l$)	Total Alpha energy of daughters (Mev/l)×(10^9)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
NH–1	25,000	210.	1:0.80:0.76	Natural	.....
NH–2	4,100	18.1	1:0.59:0.40	500	2
NH–3	2,600	7.82	1:0.39:0.21	560	3½

NOTE.—Suggested working level, 1.3×10^9 Mev; volume, 7200 cu.ft.; air requirement, 1850 cfm.

[1] Average emanation rate, 1.17×10^{11} atoms per minute per 1,000 cu. ft.

tory degree of reduction in radon and its daughters was not achieved. The reason for this was an inadequate air-change rate in the area studied, caused by placing the ventilation tube outlet too far from the face. Figure VI–1 illustrates the ventilation and sampling locations for this group of samples.

Samples NH–101 through NH–104, and NH–107. These samples, see table VI–2, were taken in the same drift as above but several months later. Because of the earlier experience, more attention was

given to the method of introduction of the dilution air to give higher effective air-change rates.

TABLE VI–2. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples NH–101 through NH–104, and NH–107]

Sample number	Radon (μμc/l)	Total alpha energy of daughters (Mev/l×10⁶)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
NH–101	58,000	367.	1:0.92:0.76	Natural	.....
NH–102	2,700	9.06	1:0.33:0.16	300	4
NH–103	55,000	361.	1:1.17:1.04	Natural	.....
NH–104	1,900	2.31	1:0.24:0.11	700	2.8
NH–107	860	1.41	1:0.21:0.09	700	5.8

NOTE.—Suggested working level, 1.3×10^5 Mev; volume, 3,000 cu. ft.; air requirement, 800 cfm.

[1] Average emanation rate, 1.18×10^{11} atoms per minute per 1,000 cu. ft.

One may note that samples NH–101 and NH–103 showed approximately the same concentrations of radon and daughter products, although in the former case the area had been undisturbed for weeks, whereas only 16 hours elapsed between samples NH–102 and NH–103.

Mathematical analyses of the situation in this area indicate that a steady state should have been reached within an hour for the air supply furnished. However, a further reduction in radon and daughter concentrations between NH–104 and NH–107 occurred, even after 2.8 hours of ventilation.

It can be calculated by the method given in this section that an air supply in the neighborhood of 800 cubic feet per minute would reduce the alpha energy concentrations of radon daughters in this drift to 1.3×10^5 Mev per liter.

Samples TN–1 and TN–2. These samples, see table VI–3, show what can be done with a churn-drill hole, unassisted by tubing, when in a very favorable location. The sampling point and drill hole were located as shown in figure VI–2.

TABLE VI–3. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples TN–1 and TN–2]

Sample number	Radon (μμc/l)	Total alpha energy of daughters (Mev/l×10⁶)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
TN–1	2,900	23.4	1:0.66:0.56	Natural	.....
TN–2	250	0.32	1:0.24:0.08	400	2.5

NOTE.—Suggested working level, 1.3×10^5 Mev; volume, 1,200 cu. ft.; air requirement, 200 cfm.

[1] Average emanation rate, 0.32×10^{11} atoms per minute per 1,000 cu. ft.

Very little ore was present in this mine, and concentrations were reduced to low values with the use of only 460 cubic feet of air per minute through the drill hole. In this situation, 250 cubic feet per minute would have been enough to reduce the alpha energy concentration of radon daughters to 1.3×10^3 Mev per liter.

Samples LV–1 and LV–2. These samples, see table VI–4, were taken in a dead-end drift which apparently was almost barren of uranium. In such situations, very little ventilation (100 cfm) is necessary to control radon daughters.

TABLE VI–4. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples LV-1 and LV-2]

Sample number	Radon (μμc/l)	Total alpha energy of daughters (Mev/l×10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
LV-1	1,500	13.6	1:0.84:0.57	Natural	.....
LV-2	80	0.01	1:0.16:0.13	450	2

NOTE.—Suggested working level, 1.3×10^3 Mev; volume, 1,200 cu. ft.

[1] Measured concentrations were too low to give statistically significant data for calculating emanation and ventilation rates. 100 cfm would be sufficient to reduce the concentration here to the working level.

Samples S–20 and S–22. These samples, see table VI–5, were taken in an artificial dead-end drift created by placing a canvas bulkhead in the drift. Samples were taken under unventilated conditions and at two rates of ventilation. The results indicate that about 700 cubic feet per minute would have been necessary to reduce the alpha energy concentration of the daughters to 1.3×10^3 Mev per liter.

TABLE VI–5. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples S-20 and S-22]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/l×10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
S-20	2,000	28.7	1:0.89:0.90	Natural	.....
S-22	360	1.42	1:0.62:0.53	660	1

NOTE.—Suggested working level, 1.3×10^3 Mev; volume, 3100 cu. ft.; air requirement, 700 cfm.

[1] Average emanation rate, 1.32×10^{11} atoms per minute per 1000 cu. ft.

Samples NH–112 and NH–113. These samples, see table VI–6, present another example of ventilation of a dead-end drift. For this radon-producing area, 600 cubic feet of air per minute were sufficient to reduce the daughter alpha energy concentration from 481×10^3 to

0.69 x 10^5 Mev per liter. From this, it appears that 450 cubic feet of air per minute would have been a borderline amount for control purposes.

TABLE VI–6. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples NH–112 and NH–113]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/l×10^9)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
NH–112	53,000	475.	1:1.13:1.10	Natural	.....
NH–113	490	0.67	1:0.15:0.06	600	2.3

NOTE.—Suggested working level, 1.3 x 10^5 Mev; volume, 3000 cu. ft.; air requirement, 450 cfm.

[1] Average emanation rate, 4.02 x 10^{10} atoms per minute per 1000 cu. ft.

Samples NH–108, NH–109, and NH–111. These samples, see table VI–7, were taken in a stope adjacent to, and continuous with, a drift with a total volume of about 7000 cubic feet. In the ventilation of this space, the tubing outlet was at the far side of the stope so that good circulation was achieved. For this case, 400 cubic feet of air per minute appeared to be about the minimum practicable amount of ventilation at the working face.

TABLE VI–7. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples NH–108, NH–109 and NH–111]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/l×10^9)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
NH–108	55,000	444.	1:0.94:0.83	Natural	.....
NH–109	700	0.93	1:0.13:0.07	800	2.5
NH–111	470	0.78	1:0.17:0.07	800	5.5

NOTE.—Suggested working level, 1.3 x 10^5 Mev; volume, 7000 cu. ft.; air requirement, 400 cfm.

[1] Average emanation rate, 1.01 x 10^{10} atoms per minute per 1000 cu. ft.

Samples Sp–4 through Sp–6. These samples, see table VI–8, were taken in a small room, approximately 5,000 cubic feet in volume. The area showed a rather high rate of production of radon, indicated by the concentrations of the radioactive contaminants existing during ventilation by 1,200 cubic feet of fresh air per minute.

For the manner in which the ventilation was supplied, it appeared that 1,000 cubic feet of air per minute would have been the minimum consistent with satisfactory reduction.

TABLE VI–8. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples Sp–4 through Sp–6]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/DC10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
Sp–4	33,000	132.	1:0.86:0.82	Natural	.....
Sp–5	600	2.66	1:0.87:0.51	900	2
Sp–6	330	0.85	1:0.42:0.31	1,200	1.2

NOTE.—Suggested working level, 1.3 x 10⁹ Mev; volume, 5000 cu. ft.; air requirement, 1000 cfm (based on higher emanation rate).

[1] Average emanation rates, 1.83 x 10¹¹ and 9.86 x 10¹⁰ atoms per minute per 1000 cu. ft., respectively.

Samples Sp–7 through Sp–9. These samples, see table VI–9, illustrate the ventilation of a very small room which might have been classified as a dead-end drift. The low rate of production of radon in this area is shown by the results in samples Sp–8 and Sp–9, in which the average radon daughter concentration was eventually reduced to less than one-tenth of the suggested level.

In the return air stream, however, contamination from cross-drifts, side-drifts, and stopes was sufficient to raise rapidly the daughter concentration to more than 10 times the suggested level. Ventilation of more spaces in the mine could be expected to reduce further the concentrations in the main passageways.

TABLE VI–9. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples Sp–7 through Sp–9]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/DC10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
Sp–7	9,000	102.	1:0.89:0.67	Natural	.....
Sp–8	130	0.30	1:0.46:0.46	1,000	2
Sp–9	<30	0.16	1:0.70:0.53	1,000	3.5

NOTE.—Suggested working level, 1.3 x 10⁹ Mev; volume, 2,500 cu. ft.; air requirement, 500 cfm.

[1] Measured concentrations were too low for use in computing emanation and ventilation rates. However, it would appear that 500 cfm would be sufficient to control the hazard here.

Samples LP–1 and LP–2. These samples, see table VI–10, were taken in a stope with two entrances, allowing good circulation of fresh air. This series demonstrated a very good reduction with the use of a rather small amount of air.

Although reductions of this magnitude cannot normally be expected with such nominal ventilation, the fact that such reductions sometimes occur shows the remarkable benefits which even a minor effort

toward supplying fresh air may occasionally achieve. In this example, 350 cubic feet of air per minute would have been sufficient to reduce the alpha energy concentration of the radon daughter products to 1.3 x 10^5 Mev per liter.

TABLE VI–10. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples LP–1 and LP–2]

Sample number	Radon (*uuc*/l)	Total Alpha energy of daughters (Mev/l)X(10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
LP–1	11,000	93.7	1:0.94:0.90	Natural	.....
LP–2	810	1.81	1:0.27:0.20	350	3

NOTE.—Suggested working level, 1.3 x 10^5 Mev; volume, 8000 cu. ft.; air requirement, 350 cfm.

[1] Average emanation rate, 1.62 x 10^{10} atoms per minute per 1000 cu. ft.

Samples S–8 through S–10, and S–14 through S–16. These samples, see table VI–11, were taken in an attempt to show the changes produced by an increase in the rate of ventilation. In samples S–15 and S–16, the concentration of the radon, as predicted by theory, is inversely proportional to the rate of ventilation. In this small room, only 200 cubic feet of air per minute would be required to reduce daughter alpha energy concentrations to less than 1.3 x 10^5 Mev per liter.

TABLE VI–11. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples S–8 through S–10 and S–14 through S–16]

Sample number	Radon (*uuc*/l)	Total Alpha energy of daughters (Mev/l)X(10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
S–8	5,900	40.4	1:0.87:0.84	Natural	.....
S–9	440	1.51	1:0.58:0.59	180	5
S–10	510	1.12	1:0.59:0.54	180	[2] 0.5
S–14	5,700	44.2	1:0.76:0.66	Natural	.....
S–15	830	3.52	1:0.57:0.43	135	3
S–16	330	0.85	1:0.46:0.36	360	[2] 1

NOTE.—Suggested working level, 1.3 x 10^5 Mev; volume, 1800 cu. ft.; air requirement, 200 cfm.

[1] Average emanation rate, 3.65 x 10^{10} atoms per minute per 1000 cu. ft.

[2] At new rate.

Samples D–1 through D–3. These samples, see table VI–12, show the results of limited ventilation of a room of 19,000 cubic feet. In this case, it would have been necessary to supply 2,900 cubic feet of air per minute to reduce radon daughters to acceptable levels.

TABLE VI–12. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples D–1 through D–3]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/l×10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
D–1	47,000	340	1:1:1 assumed	Natural	.....
D–2	1,200	7.80	1:0.45:0.28	210	2.7
D–3	1,000	3.48	1:0.30:0.11	410	[2] 2.0

NOTE.—Suggested working level, 1.3 x 10⁹ Mev; volume, 19,000 cu. ft.; air requirement, 2,900 cfm.

[1] The data here indicate that a steady state had not yet been reached, with a total of only 4.4 air changes having taken place. The emanation rate cannot be determined by analyzing the daughter energies nor by determination through the simple limiting case equation R=Q(inf)v. Instead, the more complex relationship (36) $Q(t)=\frac{R}{V}+\left[Q(o)-\frac{R}{V}\right]e^{-\alpha}$ must be used together with the data from D–2 and D–3 only.

[2] At increased rate.

Samples D–5 through D–7. These samples, see table VI–13, give the results of the ventilation of a room of 50,000 cubic feet with only 360 cubic feet of air per minute.

TABLE VI–13. *Effect of ventilation on concentration of radon and radon daughters* [1]

[Samples D–5 through D–7]

Sample number	Radon (μμc/l)	Total Alpha energy of daughters (Mev/l×10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
D–4	60,000	340	1:1.07:0.97	Natural	.....
D–6	4,900	61.2	1:0.48:0.18	360	1.5
D–7	4,200	32.5	1:0.71:0.51	360	2.5

NOTE.—Suggested working level, 1.3 x 10⁹ Mev; volume, 50,000 cu. ft.

[1] The data here show that slightly more than one air change had taken place in the 2.5 hours. This would not permit the calculation of the emanation rate, since a steady state had not been reached.

Samples LB–1 through LB–5. These samples, see table VI–14, were taken to determine the time actually necessary for concentrations of radon and its daughter products to reach a steady state with minimum ventilation. The room in which the experiment was conducted was approximately 12,500 cubic feet in volume.

The results showed that a steady state was attained during the fourth hour of ventilation. At a higher rate it would be expected that the steady state would be reached earlier. A total of 600 cubic feet of air per minute would appear to be the minimum amount of ventilation necessary for this space.

TABLE VI–14. *Effect of ventilation on concentration of radon and radon daughters*[1]

[Samples LB–1 through LB–6]

Sample number	Radon (uc/l)	Total Alpha energy of daughters (Mev/l×10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
LB–1	11,000	61.9	1:0.86:0.77	Natural	.....
LB–2	2,200	10.3	1:0.82:0.30	440	1
LB–3	1,300	3.14	1:0.36:0.10	440	2
LB–4	1,000	2.41	1:0.37:0.14	440	3
LB–5	1,000	2.48	1:0.38:0.15	440	4

NOTE.—Suggested working level, 1.3 x 10⁹ Mev; volume, 13,300 cu. ft.; air requirement, 440 cfm.

[1] Average emanation rate, 7.94 x 10⁸ atoms per minute per 1000 cu. ft.

Samples Sp–1 through Sp–3. A condition that unfortunately exists in many mine areas is shown in table VI–15. This series of samples was taken in a small room which had an opening of 5 feet by 5 feet into a level with thousands of feet of workings, a condition which made the room a relatively large one.

Although smoke movement showed that the main air movement by-passed the opening, it was obviously the contamination from this source which made it impossible to reduce the concentration of radon or its daughter products to an acceptable level at the indicated ventilation rate.

Under such conditions, very large amounts of air are required to reduce radon daughters in a single mine location to an acceptable level. The sample counts point to the advantage of sealing-off large areas that are inactive to prevent contamination of active areas.

Comment.—The results of these experiments in dead-end drifts, small rooms, and small stopes show eleven series which had radon daughter concentrations prior to ventilation varying from less than the suggested level to 440 times that level.

TABLE VI–15. *Effect of ventilation on concentration of radon and radon daughters*

[Samples SP–1 through SP–4]

Sample number	Radon (uc/l)	Total Alpha energy of daughters (Mev/l×10⁹)	Equilibrium ratio	Ventilation in cubic feet per minute (cfm)	Time in hours
Sp–1	14,000	108.	1:1.12:1.03	Natural	.....
Sp–2	900	4.46	1:0.79:0.74	1,000	1.0
Sp–3	810	3.53	1:0.77:0.66	1,000	2.0

NOTE.—Suggested working level, 1.EX10⁹ Mev; volume, not measurable.

For these samples, the calculated rates of ventilation which would reduce daughter alpha energy concentrations to the suggested level were, respectively, one air change every 4 minutes, one every 4.5 minutes, one every 5 minutes, one every 12.5 minutes, one every 4.5 minutes, one every 8 minutes, one every 17.5 minutes, one every 5 minutes, one every 7 minutes, one every 14 minutes, and one every 9 minutes.

Tables VI–12 through VI–15 give the results of ventilation experiments in four large underground rooms. For these samples, the calculated air-change rates necessary to reduce daughter alpha energy concentrations to the suggested level were, in the two cases where ventilation rates could be calculated, one change every 6 minutes and one every 20 minutes.

It was apparent that ventilation requirements for dead-end drifts, small rooms and stopes, and large rooms differ only as the emanation rate varies. The ventilation capacity was not sufficient to reduce the daughter concentration in these areas to acceptable levels. However, the value of even small amounts of ventilation was strikingly demonstrated.

Distance of Tubing from Face

The six samples referred to in table VI–16 were taken to determine the effect of ventilating with tubing at different distances from the face. The results showed considerably greater reductions at shorter distances. It is standard good ventilation practice to deliver the air within 30 feet of the working area.

TABLE VI–16. *Effect of ventilation on concentration of radon and radon daughters*

[Samples S–11 through S–13 and S–17 through S–19]

Sample number	Radon (pCi/l)	Total alpha energy of daughters (Mev/l x 10⁵)	Equilibrium ratio	Ventilation in cubic feet per minute (m³/s)	Distance from face in feet
S–11	4,200	25.4	1:0.58:0.36	Natural	.....
S–12	330	1.55	1:0.62:0.44	250	30
S–13	440	1.89	1:0.42:0.32	250	15
S–17	4,900	26.3	1:0.70:0.73	Natural	.....
S–18	3,100	4.61	1:0.52:0.36	540	60
S–19	390	1.82	1:0.56:0.42	540	30

NOTE.—Suggested working level, 1.3 x 10⁵ Mev; suggested distance from face, less than 30 feet.

Natural Ventilation

Natural ventilation has been the primary method of introducing fresh air into uranium mines. The concentrations of radioactive elements found show that natural ventilation, as practiced, is not a dependable method of controlling atmospheric contamination.

In many instances only one air opening is provided. In other cases, the difference in elevation between the collars of upcast and downcast shafts is slight, and the open area of ventilation raises is small. All these factors restrict the natural air movement that could be obtained in the mines by good design.

The results of mine samples are given in this section, together with a discussion of the factors that govern the ventilation of mines by natural air movements. The data and other information given will enable mine operators to estimate the effectiveness of natural ventilation in a particular situation.

It was realized that all samples in this study had been taken in the summer when the poorest natural ventilation would ordinarily be expected, and consequently the highest radon concentrations. Samples taken in nine Utah mines in December 1953 by the Utah State Department of Health showed concentrations to average only 45 percent of those found in similar samples taken during the preceding summer.

TABLE VI–17. *Effect of natural ventilation on concentration of radon and radon daughters*

Sample number	Radon ($\mu\mu c/l$)	Total alpha energy of daughters (Mev/l x 10^6)	Equilibrium ratio	Remarks
HT–201	28,000	156.	1:0.68:0.48	Dead-end drift, lower level.
HT–202	7,300	14.8	1:0.39:0.28	Air movement from old workings.
D–201	9,200	76.9	1:0.95:0.83	150 feet from drill hole.
V–201	2,400	13.1	1:0.71:0.54	Slusher stope.
TN–201	54,000	328.	1:0.99:0.78	425 feet from drill hole.
TN–202	3,900	28.8	1:0.79:0.66	Beneath raise.
LP–201	3,700	22.0	1:0.72:0.58	100 feet from shaft.
BC–201	970	7.23	1:0.62:0.43	Bottom incline, 50 feet from drill hole.
LP–6–201	12,700	95.9	1:1.31:1.24	Beneath raise.
LP–6–202	3,900	19.1	1:0.67:0.57	100 feet from drill hole.
MJ–201	7,900	49.4	1:0.75:0.63	Lower level.
MJ–202	7,300	26.5	1:0.95:0.89	Upper level, 200 feet to incline.

NOTE.—Suggested working level, 1.3×10^5 Mev.

The 12 samples listed in table VI–17 were taken during January 1954 in eight mines without mechanical ventilation. These mines had also been studied in the summer of 1953.

The samples are not directly comparable with those obtained during the summer in the same mines because of the changes in exposed ore bodies and size of open areas. Therefore, the only observations that

can be made are that the equilibrium ratios indicated that natural ventilation was providing some air changes and, in general, the concentrations found in the winter were lower than those determined in the summer.

It is also apparent that in the mines studied, the natural ventilation was not sufficient even in the winter to lower to the recommended levels the atmospheric concentrations of radon daughters.

The following discussion of factors that theoretically govern air movement in underground mines (*39*) explains the results shown in table VI–17 and gives information which will assist in designing natural mine ventilation systems.

Design of Natural Ventilation Systems.—The weight flow of air through a circuit is constant and if the air density remains constant the quantity of flow in cubic feet per minute remains constant throughout the circuit. In a mine ventilating circuit, differences in elevations and temperatures produce small changes in density and the quantity of flow is only approximately constant throughout the circuit although the same number of pounds of air enter and leave the mine.

The stack effect produced in a mine when the outside temperature is lower than the mine temperature is due to the difference in weight of the warm air in the mine and the cooler outside air. This pressure difference acting at any instant is known as the draft.

The difference in elevation of mine inlet and outlet directly influences the production of draft. As the column of warm air in the mine is less dense than a similar column of cool air outside, the pressure inside the mine near the lower inlet is less than that outside.

This principle may be illustrated with the use of an inverted syphon as shown in figure VI–3. The two columns represent the inlet and

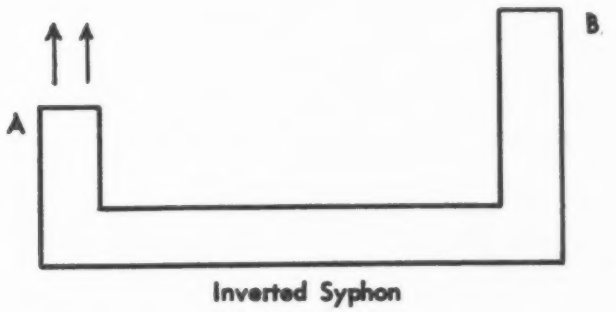


FIGURE VI–3.—*Inverted syphon illustrating a ventilation principle; see text.*

outlet collars of the mine. The imaginary column B is more dense than column A; this situation in effect raises the height of B over A and thus an overflow will occur at the top of column A.

It is well to bear in mind that the amount of air moved by stack effect will vary directly with the area of the stack cross section, and is proportional to the square root of the height of the stack. To double the capacity of a stack by increasing the height would require a stack four times as high. The same effect of doubled capacity can be obtained by doubling the area of the stack.

The quantity of air that will flow through mine openings because of stack effect is proportional to the square root of the draft head, or approximately:

$$Q=9.4\,A\sqrt{h|t_m-t_o|}$$

where,

Q: airflow in cubic feet per minute.
A: free area of inlets or outlets in square feet.
h: height from inlet to outlet in feet.
t_m: average temperature (°F.) of mine air in height h.
t_o: outside temperature (°F.).
$|t_m-t_o|$: absolute difference.
9.4: constant of proportionality, including a value of 65 percent for effectiveness of openings. This should be reduced to 50 percent with a constant of 7.2 if conditions are not favorable.

The theoretical available draft due to stack effect in a mine has been estimated with apparent satisfaction in the past by means of the formula:

$$D=0.255HP_b\left(\frac{1}{T_o}-\frac{1}{T_m}\right)$$

where,

D: draft produced by stack effect in inches of water gage.
H: difference in height between inlet and outlet in feet.
P_b: existing barometric pressure in inches of mercury.
T_o: temperature of atmosphere in absolute degrees (460° + °F.).
T_m: temperature of mine air in absolute degrees (460° + °F.).

With the quantity of airflow constant, every change in area of cross section requires a corresponding change in average velocity and in average velocity pressure. The velocity pressure, for constant quantity, changes only with the area of cross section, but the static pressure, on the other hand, is influenced by changes in both area and energy.

In an airway of uniform cross section, the velocity distribution remains practically uniform and likewise the average velocity pressure; thus the static pressure changes, or friction losses, equal the total

pressure changes. Because static pressure changes are the basic pressure measurements, and because airways of uniform area are the rule rather than the exception in commercial airflow installations, the whole subject of energy loss and energy gain involved in airflow usually will be found to be presented on an artificially simple basis of static pressure changes rather than of total pressure changes. Velocity pressures are not to be ignored, but they are considered by means of separate conventions determined by the particular conditions. In small mines where an effort is made to ventilate by means of churn-drill holes of small cross section, velocity pressures will become significant.

The friction pressure losses in mine ventilation comprise the major part of the pressure losses, and often account for 70–90 percent of the total pressure losses sustained in the system.

The basic equation for determining head loss due to friction in a mine is:

$$H_f = \frac{k\,p\,l\,v^2}{5.2A} \times \frac{d}{0.075}$$

where,

H_f: head loss due to friction in inches of water gage.
k: friction factor.
p: perimeter of cross section in feet.
l: length of air course in feet.
v: velocity of ventilating air in feet per minute.
A: area of cross section in square feet.
d: existing air density, 0.063 at 6,000 feet.
0.075: air density under standard conditions in pounds per cubic foot.

To be applicable to square cross sections in the Rocky Mountain area, the equation has been simplified to:

$$H_f = \frac{0.646\,k\,l\,v^2}{\sqrt{A}} = \frac{0.646\,k\,l\,q^2}{A^{2.5}}$$

where density when corrected for average conditions of 6,000-foot elevation, becomes 0.063 pound per cubic foot, and

k: friction factor, assumed to be 135×10^{-10}.
q: quantity of airflow in cubic feet per minute.

By utilizing this simplified equation table VI–18 has been compiled to show the friction loss in inches of water per 1,000 feet of airway with various cross-sectional areas and velocities of ventilating air.

TABLE VI–18. *Values of H_f, resistance pressure in inches water gage for 1,000 feet of air course, for mines at 6,000 feet elevation, with friction factor of 135 (10^{-10}) for ventilating air of various velocities*

Ventilating air in feet per minute	Values of H_f for different cross-sectional areas measured in square feet						
	9	16	30	36	42	49	64
500	0.727	0.546	0.398	0.364	0.337	0.311	0.273
475	.655	.491	.359	.328	.303	.280	.247
450	.590	.443	.323	.295	.273	.253	.222
425	.527	.397	.289	.263	.244	.225	.198
400	.466	.349	.255	.232	.216	.199	.175
375	.409	.307	.224	.204	.189	.175	.153
350	.357	.267	.194	.177	.165	.152	.133
325	.308	.231	.168	.153	.143	.131	.115
300	.263	.196	.144	.131	.122	.112	.098
275	.221	.165	.121	.110	.102	.094	.082
250	.183	.137	.100	.091	.084	.078	.067
225	.147	.110	.081	.074	.068	.063	.055
200	.117	.087	.064	.059	.054	.050	.043
175	.090	.067	.049	.045	.042	.038	.034
150	.066	.049	.036	.033	.030	.027	.025
125	.046	.034	.025	.023	.021	.020	.017
100	.029	.022	.016	.014	.013	.012	.011
75	.016	.012	.009	.008	.007	.007	.006
50	.007	.005	.004	.004	.004	.004	.003

NOTE.—Multiply H_f by 1.20 for total pressure loss, which includes such factors as velocity pressure and shock pressure losses.

Table VI–19 gives the amounts of air which will flow in air courses of various areas against a resistance pressure of one inch of water gage per 1,000 feet of air course. These values which are termed "capacity volumes" were calculated using a friction factor of 135 x 10^{-10}.

TABLE VI–19. *Capacity volume (q_c) related to air course area*

Air course in square feet	Capacity volume (q_c) in cubic feet per minute	Air course in square feet	Capacity volume (q_c) in cubic feet per minute
9	4,970	52	34,100
16	10,820	49	41,400
30	22,300	64	58,000
36	28,000		

Since airflow is proportional to the square root of resistance pressure, the following formula with appropriate values from tables VI–18 and VI–19 determines the available or measured airflow in a mine:

$$q_o = q_c \sqrt{H_f}$$

where,

q_o: available or measured total mine air volume in cubic feet per minute.

q_c: capacity volume or volume of air that would pass through the mine at one-inch water gage in cubic feet per minute (table VI–19).

H_f: resistance pressure in inches water gage per 1,000 feet of air course (table VI–18).

Table VI–20 contains temperature conditions on the Colorado Plateau from which temperature factors for the draft and airflow equations have been computed.

TABLE VI–20. *Average monthly temperature variations and computed temperature factors, mine air temperature of 55° F. assumed*

Month	Average temperature in degrees Fahrenheit	$t_m - t_o$, degrees Fahrenheit	$\sqrt{t_m - t_o}$	$\left(\frac{1}{T_o} - \frac{1}{T_m}\right) \times 10^{-4}$
January	25.3	29.7	5.45	12.0
February	33.3	21.6	4.65	9.0
March	43.5	11.5	3.40	4.8
April	52.3	2.7	1.64	1.5
May	61.1	−5.1	−2.26	−2.0
June	64.3	−9.3	−3.05	−3.0
July	65.0	−10.0	−3.16	−3.5
August	63.0	−10.0	−3.16	−3.5
September	63.0	−8.0	−2.83	−3.0
October	53.6	1.4	1.19	1.0
November	40.2	14.8	3.85	6.0
December	28.0	27.0	5.19	10.0

NOTE.—Average monthly temperature variations were computed from daily mean temperatures recorded by U. S. Weather Bureau 1899-1941 at Grand Junction, Colo. Negative sign indicates direction of flow.

For the purpose of discussion, let it be assumed that the average uranium mine on the Colorado Plateau consists of 275 feet of drift or air course of minimum cross-sectional area of 42 square feet. It is assumed further that upcast and downcast mine collars exist with a difference in elevation of these collars of 40 feet, either produced or occurring because of the topography. For design purposes, it must be assumed that minimum temperature differential conditions exist. Table VI–20 represents these conditions as occurring during the month of October.

Thus,

(1) The frictionless airflow due to stack effect would be:

$$Q = 9.4\ A\ \sqrt{h|t_w - t_o|}$$
$$= (9.4)\ (42)\ (6.3)\ (1.19)$$
$$= 2960 \text{ cubic feet per minute}$$

(2) The draft produced by stack effect would be:

$$D = .255\ (40)\ (25.2)\ (1)\ 10^{-4}$$
$$= .00257 \text{ inch of water gage}$$

Since values of H_f in table VI–18 have been computed for 1,000 feet of air course, the calculated draft produced will overcome a mine resistance of .00257/275 (1,000) or .00935 inch of water gage per 1,000 feet of air course. Therefore, from table VI–18, it would appear that an approximate air velocity of 80 feet per minute will be maintained in the air course by virtue of the draft produced, with an airflow of 3,360 cubic feet per minute.

The best temperature differential conditions exist during the month of January (table VI–20), at which time similar calculations show that approximately 275 feet per minute air velocity will be maintained in the air course by virtue of the draft produced and the airflow in the mine would be 11,400 cubic feet per minute.

Summary of Results

The results from all of the samples have been summarized in table VI–21. This group of samples includes a few that have not been referred to previously. It will be noted that details have been added on the concentrations of the daughter products of radon as well as on the conditions under which the samples were taken.

TABLE VI-21. *Summary of mine ventilation experiments*

Sample number	Radon	RaA	RaB	RaC	Total alpha energy of daughters (Mev/l x 10^9) suggested working level: 1.3 x 10^9 Mev/l	Ventilation in cubic feet per minute	Equilibrium ratio	Remarks
	Micromicrocuries per liter							
D-1	47,000	43,000	43,000	43,000	549	Natural	1:1:1 assumed	Room, 19,000 cu. ft., very late count.
D-2	1,200	1,300	610	380	7.60	210	1:0.45:0.28	Room, 19,000 cu. ft., 2¾ hr. vent.
D-3	1,000	910	270	100	3.46	410	1:0.30:0.11	Room, 19,000 cu. ft., 2 hr. at increased rate.
D-5	40,000	42,000	45,000	40,000	546	Natural	1:1.07:0.97	Room, 50,000 cu. ft.
D-6	6,900	7,300	4,600	4,100	61.2	360	1:0.65:0.56	Room, 50,000 cu. ft., 1½ hr. vent.
D-7	4,200	4,100	3,000	2,600	37.8	360	1:0.71:0.61	Room, 50,000 cu. ft., 2½ hr. vent.
NH-1	25,000	19,000	19,000	15,000	210	Natural	1:0.89:0.76	Dead-end drift.
NH-2	4,100	2,800	1,500	1,000	18.1	300	1:0.59:0.40	Dead-end drift, 2 hr. vent.
NH-3	2,600	1,600	620	330	7.82	300	1:0.39:0.21	Dead-end drift, 3¾ hr. vent.
NH-4	12,000	15,000	8,400	6,700	110.5			
TN-1	2,000	3,000	2,000	1,700	25.4	Natural	1:0.66:0.56	Dead-end drift.
TN-2	250	89	24	8.2	0.32	400	1:0.24:0.06	Dead-end drift, 2½ hr. vent.
LP-1	11,000	8,600	7,700	6,600	93.7	Natural	1:0.94:0.80	Stope, 5,000 cu. ft.
LP-2	510	370	100	73	1.51	280	1:0.27:0.20	Stope, 5,000 cu. ft., 3 hr. vent.
S-1	3,100	2,000	1,700	1,700	22.1	Negligible	1:0.88:0.86	In room used for S-7 to S-16. Mine entrance sealed overnight.
S-2	3,300	2,700	2,200	2,000	27.8	Negligible	1:0.82:0.76	Same as S-1, but dust introduced into air ½ hr. before sampling.
S-3	4,000	2,600	2,200	1,900	27.2	Negligible	1:0.84:0.73	Mine entrance and churn-drill holes again closed overnight.
S-7	230	300	200	100	2.21	260	1:0.66:0.35	Room, 1,800 cu. ft., 1½ hr. vent. Sampled at room entrance.
S-8	5,500	3,600	3,200	3,000	40.4	Natural	1:0.87:0.84	Room, 1,800 cu. ft.
S-9	440	190	110	110	1.51	150	1:0.58:0.59	Room, 1,800 cu. ft., vent. as in S-7, sampled at room entrance, 5 hr. vent.
S-10	510	140	85	77	1.12	180	1:0.59:0.54	Room, 1,800 cu. ft., ¾ hr. at new rate, other as in S-9.
S-11	4,500	2,900	2,500	2,700	33.4	Natural	1:0.88:0.94	Room, 1,800 cu. ft.
S-12	330	540	370	350	4.85	210	1:0.68:0.64	Room, 1,800 cu. ft., vent. tube 30 ft. from face, 2½ hr. vent. Sampled 6 ft. from face.

S-13	440	210	95	67	1.23	210	1:0.45:0.32	Room, 1,800 cu. ft., vent tube 15 ft. from face, ¼ hr. vent. at new location, same sampling point.
S-14	5,700	4,600	3,500	3,100	44.2	Natural	1:0.76:0.66	Room, 1,800 cu. ft.
S-15	820	490	280	210	3.52	125	1:0.57:0.43	Room, 1,800 cu. ft., vent tube 15 ft. from face. Sampling point at room entrance. 3 hr. vent.
S-16	320	140	64	50	0.85	360	1:0.46:0.36	Room, 1,800 cu. ft., vent tube 15 ft. from face. Sampling point at room entrance. 1 hr. at new rate.
S-17	4,800	3,600	2,800	2,700	36.3	Natural	1:0.79:0.75	Artificial dead-end drift (bulkhead in drift).
S-18	2,100	420	350	360	4.61	520	1:0.83:0.64	Same as S-17. Tube 40 ft. from "face." Sampling point 6 ft. from "face." 2½ hr. vent.
S-19	260	150	99	97	1.32	520	1:0.64:0.63	Same as S-17. Tube 20 ft. from "face." Sampling point 6 ft. from "face." 1½ hr. vent. at new location.
S-20	2,000	3,300	3,000	3,000	38.7	Natural	1:0.89:0.90	Same as S-17.
S-22	360	180	110	94	1.42	600	1:0.62:0.53	Same as S-17. Tube 20 ft. from "face." Sampling point 6 ft. from "face." 1 hr. at new rate.
S-23	4,800	6,300	6,300	5,800	78	Negligible	1:1.01:0.91	Sampling in drift which had been sealed 8 days.
LB-1	11,000	6,000	4,800	4,600	61.9	Natural	1:0.80:0.77	Room, 12,500 cu. ft.
LB-2	2,200	1,200	820	650	10.3	400	1:0.63:0.50	Room, 12,500 cu. ft., 1 hr. vent.
LB-3	1,300	760	280	140	3.54	400	1:0.36:0.18	Room, 12,500 cu. ft., 2 hr. vent.
LB-4	1,000	770	280	110	3.41	400	1:0.37:0.14	Room, 12,500 cu. ft., 3 hr. vent.
LB-5	1,900	660	170	99	2.48	400	1:0.26:0.15	Room, 12,500 cu. ft., 4 hr. vent.
NH-101	58,000	51,000	47,000	39,000	567	Natural	1:0.92:0.76	Dead-end drift, 10′ x 12′.
NH-102	2,700	2,100	700	340	9.06	300	1:0.33:0.16	Dead-end drift, 4 hr. vent.
NH-103	55,000	40,000	47,000	41,000	561	Natural	1:1.17:1.04	Dead-end drift, 10′ x 12′.
NH-104	1,500	670	160	74	2.31	700	1:0.24:0.11	Dead-end drift, 2¾ hr. vent.
NH-107	890	450	94	39	1.41	700	1:0.21:0.09	Dead-end drift, same as NH-103 and 104. 5¾ hr. vent.
NH-108	55,000	39,000	36,000	32,000	444	Natural	1:0.94:0.83	Drift and stope, 7,000 cu. ft.
NH-109	700	320	59	22	0.92	500	1:0.18:0.07	Drift and stope, 7,000 cu. ft. 2½ hr. vent.
NH-110	1,800	1,700	460	230	6.63	500	1:0.27:0.13	"Outlet" of drifts, 4½ hr. vent.
NH-111	470	280	48	19	0.78	500	1:0.17:0.07	Same as NH-109, 5½ hr. vent.
NH-112	53,000	34,000	38,000	37,000	475	Natural	1:1.13:1.10	Dead-end drift, 12′ x 7′.
NH-113	490	260	38	15	0.67	600	1:0.15:0.06	Dead-end drift, 2½ hr. vent.
Sp-1	14,000	7,900	8,900	8,300	100	Natural	1:1.12:1.05	Entrance room (vestibule) to upper level.
Sp-2	680	600	540	510	6.95	1,000	1:0.79:0.74	Entrance room (vestibule) to upper level. 1¼ hr. vent.
Sp-3	810	560	440	390	5.53	1,000	1:0.77:0.68	Entrance room (vestibule) to upper level. 2.9 hr. vent.
Sp-4	33,000	11,000	11,000	9,200	132	Natural	1:0.95:0.82	Small room, 5,000 cu. ft.
Sp-5	680	350	200	180	2.06	900	1:0.57:0.51	Small room, 5,000 cu. ft., 2 hr. vent.
Sp-6	330	150	64	47	0.85	1,200	1:0.42:0.31	Small room, 5,000 cu. ft., 1¼ hr. at higher rate.
Sp-7	9,000	9,800	8,700	6,600	102	Natural	1:0.89:0.67	Small room, 2,500 cu. ft.
Sp-8	120	44	21	21	0.30	1,000	1:0.48:0.48	Small room, 2,500 cu. ft., 2 hr. vent.

TABLE VI-21. *Summary of mine ventilation experiments*—Continued

Sample number	Radon	RaA	RaB	RaC	Total alpha energy of daughters (Mev/l x 10^5) suggested working level: 1.3 x 10^5 Mev/l	Ventilation in cubic feet per minute	Equilibrium ratio	Remarks
	Micromicrocuries per liter							
Sp-9	<10	18	14	10	0.16	1,000	1:0.76:0.55	Small room, 2,500 cu. ft. At room entrance, 3½ hr. vent.
LV-1	1,500	1,400	1,200	800	13.6	Natural	1:0.64:0.57	Dead-end drift.
LV-2	50	3.2	0.51	0.37	0.01	450	1:0.16:0.12	Dead-end drift. 2 hr. vent.
HT-201	28,000	19,000	13,000	9,200	156	Natural	1:0.68:0.48	Lower level, working face, dead-end drift.
HT-202	7,300	2,800	1,100	790	14.8	Natural	1:0.39:0.28	In drift leading to old workings, strong air movement from old workings.
D-201	9,200	6,600	6,300	5,300	76.9	Natural	1:0.95:0.83	Men mucking on lower level, 150 ft. from churn-drill hole, air movement poor.
V-201	2,400	1,500	1,100	800	13.1	Natural	1:0.71:0.54	Right hand slusher stope, fan not operating.
TN-201	54,000	28,000	28,000	22,000	328	Natural	1:0.99:0.78	Dead-end drift, men mucking, 1,000 ft. from incline, 425 ft. from churn-drill hole.
TN-202	3,900	3,000	2,300	.....	28.8	Natural	1:0.79:0.66	Under raise, 500 ft. from incline.
LP-201	3,700	2,500	1,800	1,400	22.0	Natural	1:0.72:0.58	Stope 75-100 ft. from shaft, 15 ft. from slusher.
BC-201	970	970	600	410	7.23	Natural	1:0.62:0.43	Bottom of second incline, 50 ft. from churn-drill hole, 50 ft. from slusher.
LP-6-201	12,700	6,000	7,900	7,400	95.9	Natural	1:1.31:1.24	Foot of new raise.
LP-6-202	3,900	2,300	1,900	1,300	19.1	Natural	1:0.67:0.57	Stope on upper level, 75-100 ft. from 10 in. churn-drill hole.
MJ-201	7,900	5,300	4,000	3,300	49.4	Natural	1:0.75:0.63	Lower level near slusher.
MJ-202	7,300	2,300	2,100	2,000	30.5	Natural	1:0.95:0.89	Upper level, 200 ft. from incline.

DISCUSSION

General Considerations (*40*)

The first important general requirement for ensuring safe working atmospheres in any underground mine is the provision of good general ventilation. In addition to supplying oxygen, this procedure dilutes and removes harmful dust concentrations, the products of combustion of explosives and from machinery, and gas seepage from fissures. The procedure also aids in establishing desirable temperatures and humidities.

Proper distribution of air underground demands careful thought and planning, so that clean air will be conveyed as directly as possible to the working places where it may dilute and remove harmful dust concentrations.

Abandoned or inactive workings should be completely sealed off from the fresh-air supply, while all doors and stoppings should be so constructed as to prevent leakage.

Auxiliary mechanical ventilation will provide the final mechanism by which dusty or gassy operations will be partly controlled, but unless the general ventilating system is functioning properly, the use of auxiliary units is a waste of effort. Good practice in combating hazardous exposures in underground mines dictates the installation of auxiliary mechanical ventilation in each rock heading where the working atmosphere contains hazardous substances above safe working levels.

Suitable fans delivering air through rigid or flexible tubing are necessary adjuncts to any ventilation system for uudergrouud mines.

It is apparent that specifications for mine ventilation based upon certain quantities of air per man will not be applicable in many instances. Every mine presents a different ventilation problem and controls must be designed for the specific conditions. There are large mines with perhaps 2,000 men underground at any one time; there are many more with only half a dozen men doing all the mining and development work. The fallacy of mine ventilation specifications based on any one criterion is immediately apparent.

Uranium and Hard-Rock Mining Compared (*40*)

A discussion is now indicated of the operating conditions in a uranium mine as compared with a conventional hard-rock mine. These conditions include:

1. Uranium mining differs from conventional hard-rock mining in the method of ore removal. A uranium mine rarely presents a large working or inactive stope developed as a result of ore-body extraction

utilizing sublevel cave- or sublevel stope-type mining. Room-and-pillar-type mining will be encountered with some frequency, but the usual case is what would appear to be a series of development drifts. The uranium ore body will usually occur as a narrow seam, which is extracted by following along it with a drift. Occasionally, the seam will widen out necessitating enlarging the drift-width to form a room-and-pillar operation.

2. Since uranium mines are usually one-level operations with development drifts and rooms located off a main haulageway, dust generation will be highly localized. Working areas are not generally interconnected except by passages to the main haulageway. Dust counts made on samples from working areas of such uranium mines have been much lower than expected because (a) there is no cross-contamination from one area to the other by air circulation, and (b) there is less dust-generating activity at the face of a uranium mine working area. Dust counts in uranium mines have indicated concentrations of from 5 to 20 million particles per cubic foot of air. Since the silica content of uranium ore (carnotite) ranges from 50–75 percent, it appears that generally accepted standards for control of silica dust in underground mines can be justified in uranium mining.

3. Unlike the generation of silica dust which occurs only during the working shift underground, the emanation of radon and its decay to daughters are continuous. If the ventilation equipment in a mine is turned off after a working shift, the concentration of radon and its daughters will rise to fantastic levels which must be reduced prior to re-entry into the mine. Table VI–22 illustrates the rapid growth of daughters from pure radon.

TABLE VI–22. *Growth of daughters from pure radon, per micromicrocurie of radon, with sufficient emanation of radon to maintain constant level (composite table)*

Time (minutes)	RaA	RaB	RaC	Total	Time (minutes)	RaA	RaB	RaC	Total
	Micromicrocuries					Micromicrocuries			
1	0.2035	0.0027	0	0.2062	40	1.0006	0.0023	0.2916	1.2944
2	.3653	.0101	0	.3756	50	1.0006	.0806	.3985	2.0909
3	.4946	.0210	0	.5156	60	1.0006	.7651	.4989	2.2546
4	.5975	.0346	0	.6321					
5	.6794	.0510	0.0003	.7307	120	1.0006	.9845	.8049	2.8300
					180	1.0006	.9946	.9740	2.9692
6	.7448	.0672	.0026	.8146	240	1.0006	1.0031	1.0009	3.0046
7	.7967	.0852	.0048	.8867	300	1.0006	1.0049	1.0071	3.0126
8	.8382	.1041	.0081	.9504					
9	.8712	.1234	.0114	1.0060	360	1.0006	1.0053	1.0084	3.0143
10	.8975	.1430	.0139	1.0584	420	1.0006	1.0054	1.0089	3.0148
20	.9000	.3208	.0637	1.4043					
30	.9066	.4823	.1923	1.9820					

In a gassy hard-rock mine or coal mine, the general mine ventilation system is operated continuously to remove gas as quickly as it emanates. In uranium mining, as in the mining of any gassy ore body, the ideal approach to a solution of the problem of environmental control is the continuous operation of the general mine ventilation system. The desirability is also apparent of the bratticing (isolating) of inactive areas of the mine in an effort to conserve ventilation air.

4. Another most important concept which must be borne in mind particularly with reference to ventilation is the generation in uranium mines of new daughters during the time interval required to remove the original ones. Radon daughters will grow rapidly into a mine atmosphere so long as radon is present. Since radon is constantly being emanated it can be shown for any given ventilation condition that there is a lower limit below which the radon daughter concentrations cannot be reduced. This limit is a function of the ambient radon level. The radon emanation rate is therefore the significant factor in designing uranium mine ventilation.

Calculation of Ventilation Requirements

In developing systems of mine ventilation it would be highly desirable to be able to calculate the quantities of dilution air required for each area. Several approaches using different simplifying assumptions can be used to develop procedures that would permit such calculations. One such method is presented here.

If the radon emanation rate is known for the mine or section under study, it is theoretically possible to design a ventilation system which will maintain any desired working level of radon daughters. This emanation rate in atoms per minute can be calculated by following a procedure (*35*) in which the steady state atmospheric concentration of radon is measured under known ventilation conditions. This method has certain disadvantages in that the measurement of radon must be done either in a laboratory or with costly equipment not easily taken into the field.

It is also theoretically possible to determine an emanation rate from daughter concentrations expressed in million electron volts as determined by the field method given in section V. This approach assumes that the only methods of radon daughter removal are by decay and by ventilation, that the volume and existing ventilation rate of the drift or stope under consideration are known, that the time for one complete air change under existing conditions is not more than 30 minutes or less than 2 minutes, and that a steady state exists.

Data have been presented (*36*) showing the theoretical percent of equilibrium that RaA, RaB, and RaC would have with radon at the steady state under various ventilation conditions with removal only by decay and ventilation. These data have been used to determine the ratio between the potential alpha energy from decay to RaD of the daughters which should exist under the specific conditions and the potential alpha energy from a similar decay of the daughters if they were at equilibrium with the radon.

These ratios have been plotted as percents against air changes per minute in figure VI–4. With an air-change rate for a mine area obtained from volume and air flow measurements, reference to this curve gives the theoretical percent of equilibrium that exists. From

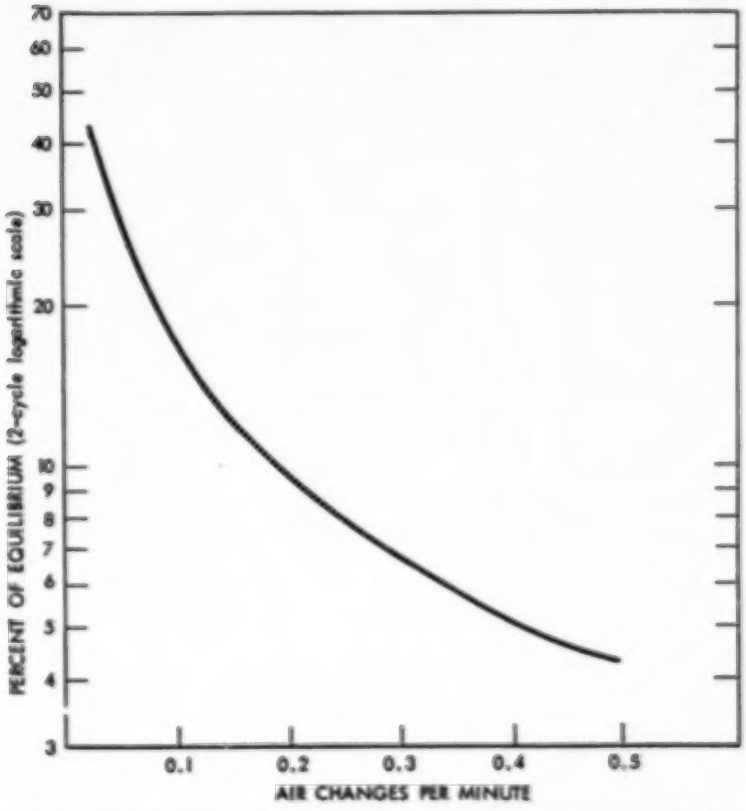


FIGURE VI–4.—*Effect of ventilation on radon-radon daughter equilibria considered on basis of alpha energy; limiting case.*

this rate and the potential alpha energy concentration as measured by the field method, it is theoretically possible to determine the radon concentration, and hence the emanation rate. This can be done by using the relationship, $R=EF$, where R is the emanation rate in atoms per minute per 1000 cubic feet; E is the measured daughter product concentration in Mev per liter; and F is a factor determined by the existing ventilation rate. (F also has built into it a series of appropriate conversion factors to make the equation dimensionally sound.) A graph of values of F for different ventilation rates is presented in figure VI–5. By taking the appropriate factor from this graph and multiplying by the total potential alpha energy of the daughters as measured under existing conditions, an apparent emanation rate is obtained in atoms per minute per 1,000 cubic feet of mine volume.

Once the emanation rate is known, the curve in figure VI–6 can be used to determine the ventilation required to reduce the ambient daughter product concentration to the desired working level of 1.3×10^5 Mev per liter.

This method adjusts for nonequilibrium conditions but does not attempt to consider daughter reduction by any means other than decay and ventilation. In practice, the wall effect of mine surfaces and the presence of dust that may settle may remove an appreciable amount of the daughters. The exclusion of the wall effect factor means that emanation rates computed from daughter concentrations may be lower than those computed from measured radon concentrations. Thus, the predicted ventilation rates needed to maintain the suggested working level will be less than those calculated from radon concentration data. However, the removal of daughters by plating out on walls may also continue under the new conditions of ventilation and thus tend to offset the error introduced by neglecting this factor. As more data are obtained it may be possible to develop empirical factors which can be used to correct for the removal of daughters by surfaces if this phenomenon is found to be of importance.

Another cause of differences between emanation rates calculated from daughter concentrations and true emanation rates can be the aspiration of contaminated air into the mine area being studied. Since the theory assumes that only clean air is used for ventilation, the introduction of contaminated air will cause the calculated emanation rate to be higher than the true value. Therefore, the predicted ventilation rate needed to maintain the suggested working level may be too high.

The above procedure was used to calculate the radon emanation rates and the ventilation air requirements listed in tables VI–1 through VI–17 in those cases where suitable data were available.

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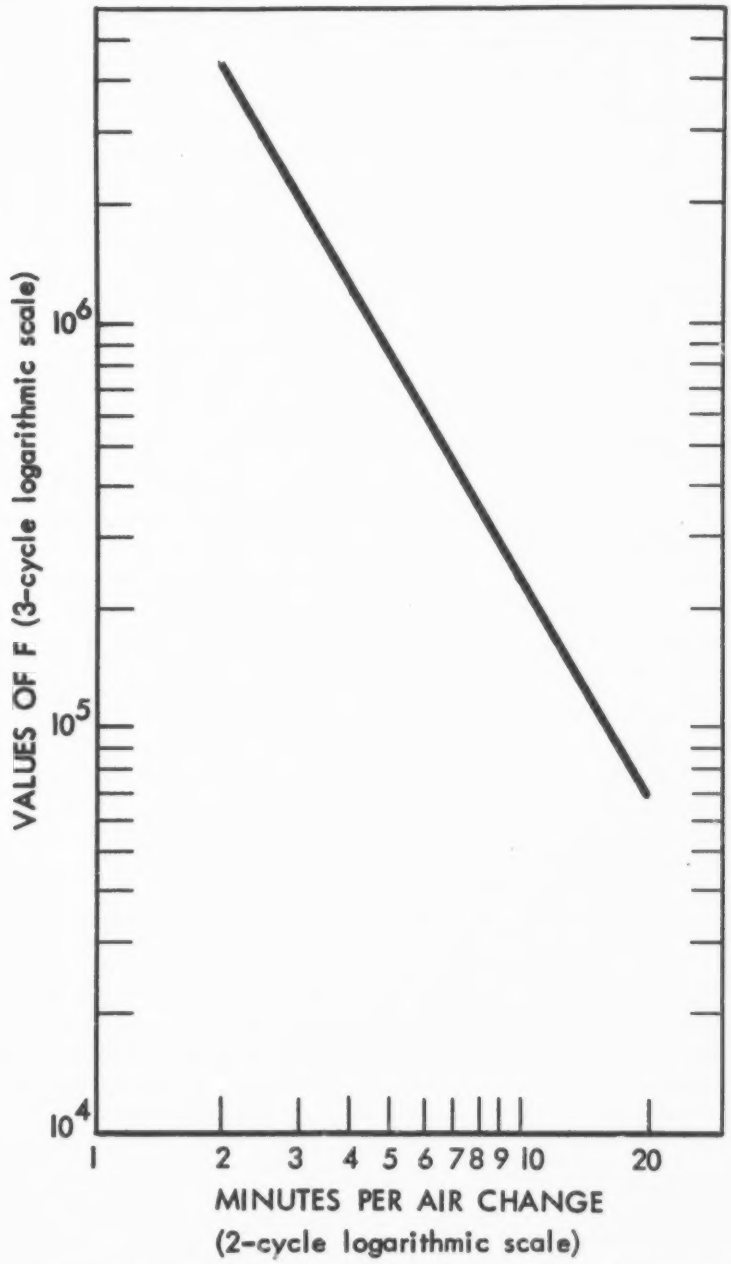

FIGURE VI–5.—*F factor for determining emanation rate in atoms per minute per 1,000 cubic feet of mine volume.*

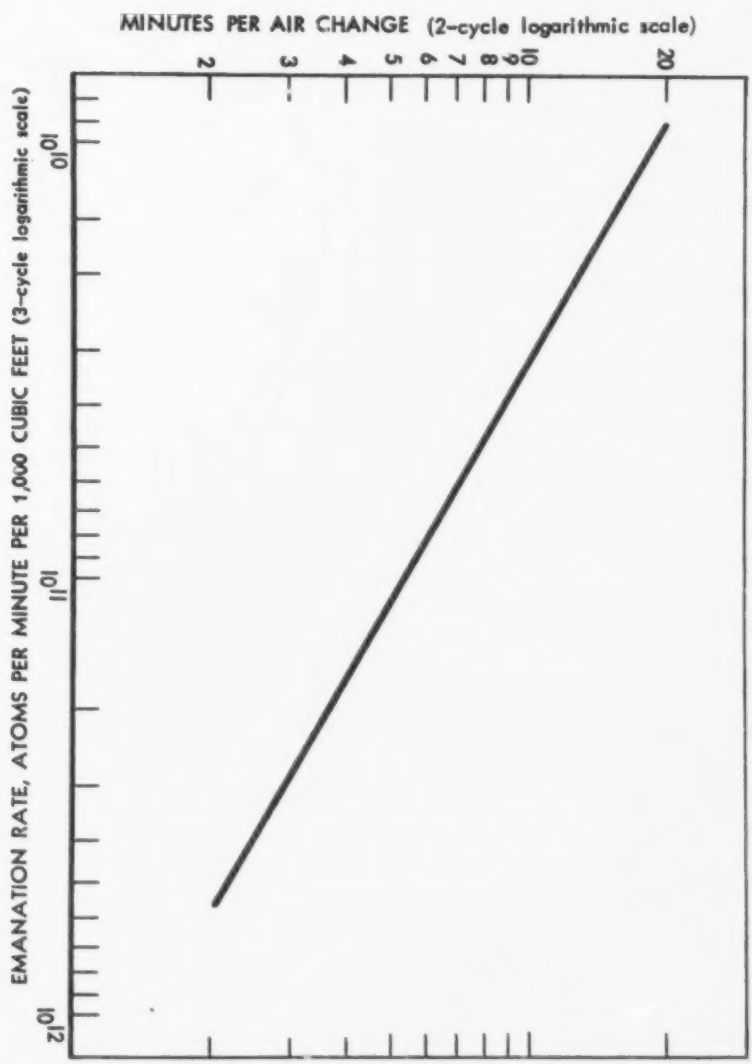

FIGURE VI–6.—*Emanation rate in atoms per minute per 1,000 cubic feet of mine volume related to time in minutes required for one air change to reduce radon daughters to working level of 1.3 × 10⁵ Mev per liter of air.*

CONCLUSIONS AND RECOMMENDATIONS

It has been pointed out that the concentration of radon and its daughter products in a particular volume depends on (1) the rate at which radon is entering the volume by diffusion from the uranium ore and by diffusion from adjoining volumes, (2) the rate at which radon and daughter products are being removed from the volume by ventilation or filtration and decay, and (3) the rate of deposition of daughter products on walls.

The concentration of radon daughter products is reduced by good ventilation practices to a much greater extent than is the radon concentration. Because of the greater potential health hazard from radon daughter products as compared to radon itself, engineering controls are designed to maintain daughter product concentration at a level of 1.3×10^5 Mev per liter of air.

The concentrations of radon and its daughter products may be predicted under various ventilation conditions on the basis of air-change rates and emanation rates.

Emanation rates have been found to vary from 1×10^7 to 1×10^{11} atoms per minute per 1000 cubic feet of mine volume, or a variation by a factor of 10,000 so far as ventilation control is concerned.

In lieu of a preliminary study to determine radon emanation rates, mines must be ventilated to control the worst expected condition, namely, an emanation rate of 1×10^{11} atoms per minute per 1000 cubic feet of mine volume.

It appears, therefore, that design specifications for ventilation in any hard-rock mine are adequate for the ventilation of uranium mines. These specifications, however, must be considered to be minimal. For uranium mines, the following recommendations are made:

1. In all working areas, sufficient ventilation should be provided to maintain the atmospheric concentration of radon daughter products below the suggested working level of 1.3×10^5 Mev of alpha energy per liter.

2. Each pair of men mining in ore should be provided no less than 1000 cubic feet of fresh air per minute, discharged from a tube outlet located not more than 30 feet from the face.

3. In drifts, the quantity of airflow should be calculated to produce a velocity of not less than 30 feet per minute.

4. In all working areas where radon is being emanated, the ventilation rate should be calculated to produce a complete air change in the area at least every 4 minutes, unless a preliminary engineering survey shows emanation rates of less than 1×10^{11} atoms per minute per 1,000 cubic feet of mine volume. In such cases, the frequency of air change may be reduced as calculated from figures VI–5 and VI–6.

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Glossary of Terms and Conversion Factors

ADSORPTION: The attachment of one substance to the surface of another.

ALPHA PARTICLE: Charged particle, having a mass of four units and two unit positive charges of electricity, which is emitted from the nucleus of some atoms. It is composed of two neutrons and two protons.

ALPHA RAY: Stream of fast-moving alpha particles. It is strongly ionizing and weakly penetrating radiation.

ALVEOLI: Plural of alveolus. Alveoli pulmonum, the air cells of the lungs.

BETA PARTICLE: Charged particle, having a mass and charge equal in magnitude to those of the electron, which is emitted from the nucleus of some atoms.

BETA RAY: Stream of high speed electrons of nuclear origin more penetrating but less ionizing than alpha rays; a stream of high speed electrons.

BRONCHI: Plural of bronchus. The two main branches of the trachea.

CARNOTITE: An uranium ore. A vanadate of uranium and potassium containing 50 to 65 percent of uranium trioxide, and about 20 percent of vanadium oxide. Found in Colorado Plateau as a yellow impregnation in sandstone.

CFM: Cubic Feet per Minute; one cubic foot equals 28.3 liters.

COLLAR: The mouth, or surface opening, of a mine shaft or bore hole.

COLORADO PLATEAU: A region covering an area of about 140,000 square miles in Colorado, Utah, Arizona and New Mexico.

CURIE (c): Measure of quantity of radioactivity; one curie equals 2.22×10^{12} disintegrations per minute.

DECAY CONSTANT: The fraction, lambda (λ), of the number of atoms of a radioactive isotope which decays in the unit time. Lambda equals 0.693/half life.

DOWNCAST (SHAFT): An opening extending to the surface through which outside air enters a mine.

DPM: Disintegrations Per Minute. DPM equals number of atoms times decay constant.

DRIFT: A horizontal passage underground. A drift follows the vein, as distinguished from a crosscut, which intersects it, or a level or gallery, which may do either.

DYNE: Force acting on a mass of one gram to produce an acceleration of one centimeter per second per second.

ELECTRON VOLT: The amount of energy required to move one electron charge through a difference of potential of one volt. The unit is equal to 1.6×10^{-12} erg.

ERG: Unit of energy which can exert a force of one dyne through a distance of one centimeter.

FACE: In any tunnel or stope, the end at which work is progressing or was last done.

GAMMA RAY: Electromagnetic radiation emitted from the nucleus of a radioactive atom.

GEOMETRY FACTOR: The fraction of the total solid angle about the source of radiation that is subtended by the face of the sensitive volume of a detector.

HALF LIFE: Time required for a radioactive substance to lose by decay 50 percent of its activity.

HEMOPOIETIC SYSTEM: The blood-making system including bone marrow, the spleen and lymph nodes.

IONIZATION: Act or result of any process by which a neutral atom or molecule acquires either a positive or negative electric charge.

IONIZING RADIATION: Radiation possessing sufficient energy to ionize the atom or molecules absorbing it.

LD_{50}: Lethal Dose 50 percent. The radiation dose required to kill 50 percent of a relatively large number of animals.

MAXIMUM PERMISSIBLE DOSE: An official figure based on the maximum dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his life, and to which a safety factor has been applied.

MEV: Million Electron Volts of energy.

MICROMICROCURIE ($\mu\mu c$): 1×10^{-12} curie; 2.22 disintegrations per minute.

RAD: RADiation. That dose of any ionizing radiation which produces energy absorption of 100 ergs per gram of absorbing material.

RADIOACTIVITY: Characteristic of certain kinds of matter, the atomic nuclei of which are unstable and undergo spontaneous disintegration with liberation of energy. The disintegration process, which usually results in the formation of new elements, is accompanied by the emission of one or more types of radiation, such as alpha particles, beta particles, and gamma rays.

RADIOACTIVE EQUILIBRIUM: Among the members of a radioactive series, the state which prevails when the ratios between the amounts of successive members of the series remain constant. *Secular equilibrium:* If a parent element has a very much longer half life than the succeeding ones, so that there is no appreciable change in its amount in the time interval required for the later products to attain equilibrium, then, after the condition is reached, equal numbers of atoms of all members of the series disintegrate in unit time. This condition is never actually attained, but is essentially established in such a case as radium and its series through Radium C. The half life of radium is 1600 years, of radon, 3.82 days, and of each of the subsequent members, a few minutes. After about a month essentially the equilibrium amount of radon is present, and then for a long time all members of the series disintegrate the same number of atoms per unit time. *Transient equilibrium:* If the half life of the parent is sufficiently short, so that the quantity present decreases appreciably during the period under consideration, but is still longer than that of successive members of the series, a stage of equilibrium will be reached, after which all members of the series decrease in amount exponentially with the period of the parent. An example of this is radon, with a half life of 3.82 days, and the successive members of the series through Radium C. (*Radiological Health Handbook*. Robert A. Taft Sanitary Engineering Center, U. S. Public Health Service, Cincinnati, Ohio, 1952.)

RADIUM A: Polonium^{218}. 9.78 atoms Po^{218} equal one micromicrocurie.

RADIUM B: Lead^{214}. 83.714 atoms Pb^{214} equal one micromicrocurie.

RADIUM C: Bismuth^{214}. 63.068 atoms Bi^{214} equal one micromicrocurie.

RADIUM C′: Polonium^{214}.

RADIUM D: Lead^{210}.

RAISE: A vertical opening which connects one level of a mine with the level above.

REM: Roentgen Equivalent Man. That quantity of ionizing radiation which when absorbed by man produces an effect equivalent to the absorption by man of one roentgen of x- or gamma-radiation.

REP: Roentgen Equivalent Physical. That dose of any ionizing radiation which produces energy absorption of 93 ergs per gram of tissue.

ROENTGEN (r): The primary unit of dose defined as that quantity of x- or gamma-radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign.

SEAM: A stratum or bed of coal or other mineral.

SHAFT: An excavation of limited area compared with its depth, made for finding or mining ore or coal, raising water, ore, rock or coal, hoisting and lowering men and material, or ventilating underground workings.

STOPE: An excavation from which the ore has been extracted, either above or below a level, in a series of steps.

STOPPING: A board, masonry or brick wall built across old headings, chutes, or airways, to confine the ventilating current to certain passages, and also to back up the gas in old workings, and in some cases to smother a mine fire.

UPCAST (SHAFT): An opening extending to the surface through which air leaves a mine.

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